Japanese Technology Evaluation Center

JTEC

JTEC Panel Report on

X-Ray Lithography In Japan

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October 1991

Coordinated by

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JAPANESE TECHNOLOGY EVALUATION CENTER

SPONSOR The Japanese Technology Evaluation Center (JTEC) is operated for the Federal Government by Loyola College to provide assessments of Japanese research and development (R&D) in selected technologies. The Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) supported this study. The National Science Foundation (NSF) is the lead support agency for all other JTEC studies. Other sponsors include the National Aeronautics and Space Administration (NASA), the Department of Commerce (DOC), the Department of Energy (DOE), and the U.S. Air Force.

PURPOSE JTEC assessments contribute to more balanced technology transfer between Japan and the United States. The Japanese excel at acquisition and perfection of foreign technologies, but the U.S. has relatively little experience with this process. As the Japanese become leaders in research in targeted technologies, it is essential that the United States have access to the results. JTEC provides the important first step in this process by alerting U.S. researchers to Japanese accomplishments. JTEC findings can also be helpful in formulating governmental research and trade policies.

APPROACH The assessments are performed by panels of about six U.S technical experts in each area. Panel members are leading authorities in the field, technically active, and knowledgeable about Japanese and U.S. research programs. Each panelist spends about one month of effort reviewing literature, making assessments, and writing reports on a part-time basis over a twelve-month period. All recent panels have conducted extensive tours of Japanese laboratories. To provide a balanced perspective, panelists are selected from industry, academia, and government.

ASSESSMENTS The focus of the assessments is on the status and long-term direction of Japanese R&D efforts relative to those in the United States. Other important aspects include the evolution of the technology, key Japanese researchers and R&D organizations, and funding sources.

REPORTS The panel findings are presented to workshops where invited participants critique the preliminary results. This report is distributed by the Defense Technical Information Center (DTIC) and by the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161 (703-487-4650). The panelists also present technical findings in papers and books. All results are unclassified and public.

STAFF The Loyola College JTEC staff members help select topics to be assessed, recruit experts as panelists, organize and coordinate panel activities, provide literature support, organize tours of Japanese labs, assist in the preparation of workshop presentations and in the preparation of reports, and provide general administrative support. Mr. Cecil Uyehara of Uyehara International Associates provided literature support and advance work for this panel.

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X-RAY LITHOGRAPHY IN JAPAN

FINAL REPORT

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This material is based upon work supported by the Department of the Navy, Office of the Chief of Naval Research (ONR) and the Defense Advanced Research Projects Agency under ONR Grant N00014-90-J-1853, awarded to the Japanese Technology Evaluation Center at Loyola College in Maryland. The Government has certain rights in this material. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Government, the authors' parent institutions or Loyola College.

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ACKNOWLEDGMENTS

The JTEC Panel on X-Ray Lithography wishes to acknowledge the support of the Office of Naval Research and the Defense Advanced Research Projects Agency for their initiation of and support for this study. This effort not only allowed the panel to gather together for an extended period and probe this fascinating area of developing microelectronics manufacturing technology, but it also gave us the opportunity to: (a) work collaboratively our fellow technical colleagues in the U.S. Government agencies, and (b) visit the research and development sites of our international technical colleagues and friends in Japan.

The execution of such a study is not an easy undertaking, and the panel is very grateful for the support of the Japanese Technology Evaluation Center (JTEC). From the inception of this study to the publication of its final written report, JTEC has been constantly at our side, offering us whatever assistance was needed to perform our technical function in a smooth and unencumbered manner.

Additionally, special acknowledgement is given to Mr. Cecil Uyehara, President of Uyehara International Associates, for logistics support prior to and during our travels in Japan. We are indebted to him for making this very busy field study run smoothly and efficiently.

Technically, the panel did not function alone; we were very fortunate to be able to expand the panel into a larger technical committee. This body was formed by the addition of the following people:

Kenneth Davis	ONR
David Patterson	DARPA
Martin Peckerar	NRL
David Nagel	NRL
Allen Lepore	AETDL

The committee supported the panel in the following ways: helping to formulate the detailed technical plans for the field study; accompanying us as we visited the 20 Japanese institutions; and providing some of the necessary technical and administrative support to the panel in the preparation of the panel's oral and written reports.

Finally, the panel wishes to acknowledge the assistance, kindness, friendship, and openness that our Japanese colleagues and counterparts gave us during the study. The acceptance of our visits, the frankness of the technical discussions, and the reviews of the draft report greatly aided the Panel in its ability to fully understand the current status of this technology development and, simultaneously, respect the

proprietary aspects of the individual positions of each industrial organization visited.

We recognize that this is another exchange of important technical information between the United States and Japan. We hope that this study contributes to a better mutual understanding and respect between the two countries.

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EXECUTIVE SUMMARY

Integrated circuits (semiconductors) are the key components of modern computers, communication systems, consumer electronics, and the new generations of "smart" machines and instruments. Japan's strong position and growing influence in the manufacture of semiconductors and systems based on them is well known and well documented. Microlithography is one of the most critical elements of the semiconductor manufacturing process because it determines the minimum feature size and the functional capabilities of the semiconductor. Because it is used many times in the manufacturing sequence, the quality of the microlithography process (i.e., number of defects, control for feature size, etc.) is critical in determining the yield and cost of semiconductors and hence the competitiveness of the electronics industry. At present all volume semiconductor manufacturing is done with optical UV (ultraviolet) projection lithography, a twenty-year-old photographic technology which has been and is still evolving.

There are many issues that limit the technical capability and cost-effectiveness of UV lithography, and thus, alternate lithographic techniques are continuously being researched and developed. X-ray lithography, which was invented in the early 1970s, holds the promise of providing higher yields in manufacturing semiconductors by virtue of enhanced process latitude, process robustness, and resolution.

In Japan, X-ray lithography has been researched since the mid-1970s, and in recent years, the existence of several large efforts at major electronics firms, nonprofit laboratories, and government laboratories has been well publicized, particularly those that involved construction of electron synchrotrons to serve as X-ray sources. The magnitude of these efforts and the absence of comparable synchrotron-based industrial efforts in the United States, except at IBM, led to widespread concern that the U.S. semiconductor industry may be bypassed in this potential key microlithographic technology.

This concern was the basis for creating an expert panel to visit the major research and development activities in X-ray lithography in Japan. The panel visited twenty companies and organizations prominent in the field, and prepared a detailed appraisal of the technology, personnel commitments, and strategies for implementation in manufacturing. A summary of the conclusions drawn from the trip follows:

1. The major Japanese microelectronics firms have a broad, well-developed strategy for research and development of microlithography technology that

includes UV, deep UV, X-ray proximity and projection, and electron-beam lithographies. They are investing in ALL of the alternatives.

All of the manufacturers that were visited either had in-house X-ray programs, were members of the SORTEC X-ray consortium, or both.

The degree of involvement varied from manufacturer to manufacturer. The manufacturing firms tend to be large and vertically integrated. Their commitment to X-ray lithography was firm and the programs appeared to be well balanced. This is in sharp contrast to the United States where with the exception of AT&T, IBM, and Motorola, there is limited interest from semiconductor manufacturers in X-ray technology.

2. The consensus among Japanese semiconductor manufacturers was that optical lithography would continue to evolve for advanced semiconductor manufacturing until the late 1990s, and that the potential switch to X-ray lithography will probably occur when the minimum critical dimension is 0.25 micron or less. While their first choice for 256 megabit DRAMs is optical, they are prepared to use X-ray technology for manufacturing if necessary.

This viewpoint is based on many factors: the past history of evolution in optics, the level of investment in optics, the technical barriers and financial investment necessary for X-ray lithography implementation, and the desire to stay with evolutionary rather than switch to a revolutionary technology. Although the potential of higher yield and lower manufacturing costs with X ray is recognized, manufacturers will not change technology until absolutely necessary. This same viewpoint is also prevalent in the United States and Europe.

3. There are many large efforts in Japan to develop synchrotron-based X-ray lithography for mass production of advanced semiconductors, and this has resulted in two operational development microlithography facilities. Others are in the construction phase. Synchrotrons for X-ray lithography usage are an accomplished fact.

All of the companies and laboratories visited by the panel are developing synchrotron-based lithography systems because they are bright, collimated sources. Smaller laser and gas plasma sources, while more desirable from a granularity standpoint, were not visible or discussed in any detail. X-ray projection projects exist; they were mentioned at several companies but were not extensively discussed.

The synchrotron source suffers from large capital costs, a lack of granularity (small-capacity increments cannot be added; a complete synchrotron must be purchased), and a requirement for special facilities and logistics support for semiconductor manufacturing. It is at the present time the only source that has demonstrated the parameters required for semiconductor manufacture. The size, cost, and configurational aspects of synchrotron-based X-ray lithography did not appear to be serious issues in Japan with the DRAM manufacturers; their view was that if X-ray lithography is to be used, it will be for large-volume manufacturing, and this will require multiple synchrotron facilities.

Cost is a major issue with the U.S. and European manufacturers since their volume semiconductor production is not DRAM-based, they are smaller companies, and many are not using the leading edge of microlithographic technology. The initial investment is beyond the means of most of these manufacturers, and only IBM, AT&T, and Motorola have major active internal X-ray programs. DARPA is administering a program sponsored and financed by Congress that is attempting to overcome some of these difficulties by helping to build the supporting infrastructure necessary for X-ray lithography. DARPA is in the process of expanding that program to support other lithographic alternatives.

In the United States, several synchrotrons originally developed for other purposes are now being used in part for X-ray lithography research and development, notably at the University of Wisconsin and Brookhaven National Laboratory. Also, efforts to develop synchrotrons for lithography are in process at Louisiana State University and at Brookhaven. IBM is presently commissioning a superconducting synchrotron designed and constructed by Oxford Instruments, a British company, at its Advanced Technology Center in Hopewell Junction, New York.

4. Development of X-ray mask technology, exposure systems, and resists is being pursued vigorously in Japan, as is the integration of the total system.

There appeared to be a consensus that materials for X-ray masks are adequate now. The Japanese are presently using silicon nitride membranes with tantalum absorber mask technology licensed from NTT. They have undertaken research on silicon carbide membrane and tungsten absorber materials. There is also planning for research on diamond membranes.

The major mask concern was 1X electron-beam mask patterning, specifically errors in feature placement and dimension control. Surprisingly, there is no work being pursued on mask inspection and repair; the Japanese believe these tools will be available for purchase from domestic or overseas sources when required.

Several independent efforts are being pursued on exposure system aligners with all critical elements under development. Heterodyne interferometric alignment techniques are favored for alignment; these are more advanced in concept than U.S. or European projects at the present time.

Beamline (beam delivery) technology development is being pursued primarily by the synchrotron user community, and there is at present no manufacturer of beamlines. They are designed and assembled by users as required.

The manufacturing system (beamlines, aligners, process, facility, etc.) will be integrated by the individual user companies. Some companies (e.g., Sumitomo Heavy Industries) are planning on supplying all elements -- aligners, beamlines, and synchrotron -- and will be in a position to do the integration if required.

5. With respect to fundamental understanding of the science of X-ray lithography, the Japanese and the U.S. technical communities are essentially on a par. However, the trend is for the Japanese to pull ahead of the U.S. due to a higher level of funding and staffing, particularly at the company level. This conclusion is consistent with the trend across all parts of the microelectronics industry.

In Japan, all the major industrial semiconductor manufacturers work in almost all phases of synchrotron-based X-ray lithography. In the United States, all semiconductor manufacturers except IBM, AT&T, and Motorola have either no effort in X-ray lithography or a subcritical one. What is perhaps more significant, the U.S. semiconductor manufacturers have an inadequate knowledge of the fundamental science of microlithography, especially of advanced techniques such as X-ray lithography. This is offset to some extent by the level of expertise in U.S. universities, which are often at the leading edge of microlithography science and technology. Technology transfer has been and is still a problem, although the situation is improving.

The university situation in Japan is not as clear, and more of the applied research appears to be going on in individual companies. It is clear that Japanese industry is in a much better position to capitalize on X-ray lithography if necessary, thereby maintaining or increasing its market share in semiconductors and the advanced systems dependent on semiconductors.

6. Most of the funding for X-ray lithography efforts in Japan comes from the individual industrial organizations. The Japanese government directly and indirectly has provided "seed" money to major research and development efforts.

In Japan, the government supports: the KEK Photon Factory (Ministry of Education); the Electrotechnical Laboratory (MITI), a source of much research and development, especially on synchrotron technology; and 70% of the SORTEC industrial consortium, which is focused exclusively on synchrotron-based X-ray lithography, a ten-year program. The government has funded roughly 70 million U.S. dollars of the SORTEC development through MITI, and industry has funded

30 million dollars. NTT, which has been the leader in X-ray lithography in Japan and stimulated much of the industrial development, is 70% government-owned. Japanese companies are making the major part of the X-ray investment in their own companies.

In the United States, there has been a significant X-ray lithography program for over ten years at IBM, which was recently joined by Motorola. The U.S. Congress has provided money to DARPA for applied research and development on X-ray lithography to all sectors of the technical and industrial community. However, the U.S. industrial community has not been independently preparing itself for insertion of X-ray lithography into manufacturing.

CHAPTER I

Overview of Proximity X-ray Lithography Research and Development in Japan

James T. Clemens

INTRODUCTION

Lithography is a science and technology that is not widely understood by the general educated public. However, it has shaped our lives more than any other technology, except for medicine.

Lithography is defined as the science and technology for the replication and/or mass production of patterns or images of any kind. Therefore, the basic methods of mass education and information communication rely upon the scientific discipline of lithography. The simplest example of lithography is the printing press. In fact, modern lithography essentially began with the invention of the printing press and the mass production of the Gutenberg Bible.

Lithography has created the books, newspapers, magazines, and journals by which we: a) learn to read, b) educate our societies, and c) store our information. It has created the modern society, which is composed of an educated population.

With the development of electricity and electronics, lithography has not been displaced from its central role in sustaining and advancing society. The electronics industry is now a chief consumer of advanced lithographic technology. The color cathode ray tube, the flat-panel display, the solar cell, the printed wiring board, and the tiny but potent integrated circuit are all produced by lithographic technologies. These are the building blocks (hardware) of telecommunication systems, computers, and almost every other advanced electronic system in existence.

Modern society is now critically dependent on electronic systems for its financial health and stability, from manufacturing to monetary management. Any society that wishes to maintain its standard of living must have access to the most advanced lithography technologies.

It is for this reason that agencies of the U.S. Government requested that this study of X-ray lithography R&D in Japan be conducted. The JTEC panel members undertook this study in the spirit of enhancing communication between the two countries' technical communities. During this study we found that the same spirit, calling for mutual cooperation, existed everywhere in Japanese society.

In order to obtain an accurate view of the X-ray lithography (XRL) R&D activities in Japan, the panel used two important mechanisms for researching the subject: first, a one-week, intensive visit to twenty identified organizations in Japan was carefully planned and executed; second, the technique of the structured interview was adopted.

A structured interview consists of compiling an extensive list of questions covering all aspects of X-ray lithography, from financial investment, to lithographic materials and equipment development, and finally, to device fabrication and testing. The formal list of questions was sent to each of the twenty institutions, and they were asked to prepare responses in each area that they *were actively researching* and developing.

This structured interview questionnaire was then used as a discussion guide during each of our visits. The panel members were quickly able to identify at each visited organization those technical areas where detailed discussions proved most valuable for information gathering. This mechanism worked quite well.

Since XRL technology has significant potential commercial value, it is logical that industrial organizations would be reluctant to discuss proprietary information. What we discovered is that many industrial organizations at the beginning of our visit requested that certain discussed information be kept confidential, and then the personnel proceeded to have very frank discussions with us. As a result, the on-site visits were extremely valuable. Accordingly, the panel's draft report was sent to each individual organization for screening, so that we did not inadvertently violate the confidentiality agreement. We gathered quite a detailed understanding of the state of XRL R&D in Japan, and were able to build an accurate picture, without having to identify any individual organization. We sincerely appreciate the efforts that our Japanese hosts gave to this project. A spirit of international cooperation between the U.S. and Japanese XRL R&D technical communities was obvious.

It is becoming evident that the "high-technology" communities of the most advanced societies of the world have fully realized that the continued well-being of each society depends upon the combined talents and intellectual resources of all societies. In particular, advancing modern lithography is an international technical challenge.

MODERN SEMICONDUCTOR LITHOGRAPHY TECHNOLOGY

The most modern or advanced lithographic technologies are applied to the fabrication of integrated circuits. The impact of lithography on integrated circuit manufacture will be reviewed in the following subsections:

a) Feature size evolution
b) The development of modern lithographic exposure systems
c) Manufacturing and cost issues
d) Integrated circuit performance issues

Feature Size Evolution

The evolution of feature size (or design rules) used in the semiconductor industry can be characterized by noting that the minimum feature size used as a function of time has been decreasing exponentially. Basically every three years, the minimum feature size has been reduced by a factor equal to 0.70. Figure 1.1 relates the minimum feature size introduced into manufacture as a function of time.

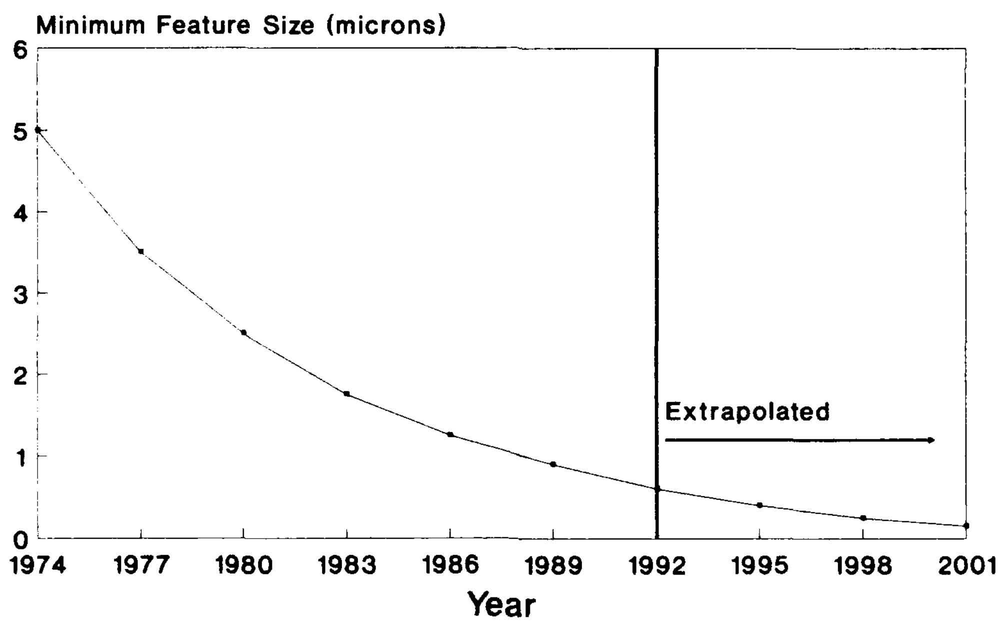


Figure 1.1. Reduction in Minimum Feature Size Over Time

The Development of Modern Lithographic Exposure Systems

In the earliest phases of semiconductor integrated circuit (IC) development ($_{ca}$1965), the lithography process started with hand-drawn master patterns that were to be used to create the small-scale IC. The master drawings were then photographically reduced in size, and a set of master glass plates was fabricated. Then, again using photographic techniques, a repeating array of each of the master masks was produced by using a high-precision step-and-repeat reduction camera. This optical camera reduced the image of the master mask, exposed it onto a second glass plate coated with a photosensitive emulsion, and then precisely stepped a given distance (Figure 1.2). Once again the camera exposed the pattern and then repeated the procedure until the entire secondary mask contained an exposed array of reduced, primary patterns. This is the basis for the name "step-and-repeat" printing, a technique that is essentially used in all modern lithographic systems.

```
Plate # 1

              +----------+
              | xxxxxxxx |
x  ->         | xxxxxxxx |
              | xxxxxxxx |
              | xxxxxxxx |
              +----------+

Plate # 2 (etc.)

              +----------+
              | zzzzzzzz |
z  ->         | zzzzzzzz |
              | zzzzzzzz |
              | zzzzzzzz |
              +----------+
```

Figure 1.2. 1:1 Mask Fabrication

Soon, however, the patterns became more complex, and hand-based techniques for creating the master patterns became limiting operations in fabrication. The new pattern data had to be handled by computers. Furthermore, electro-mechanical methods of generating the master patterns did not offer a long-term solution, due to the large databases and the associated extremely long operational times of mechanical systems.

In order to solve this problem, the technology of electron beams was employed. An electron beam could be easily focused into a very small spot size and rapidly deflected over the area where a pattern was to be defined. As a result of the need to handle large-pattern databases, the technology of computer-controlled electron beam lithography was developed in the early 1970s. This technology has proved to be the critical mask-making technology of all modern fineline lithography techniques.

The step-and-repeat camera (for mask making) was no longer needed due to availability of the new electron beam machines, but this technology did not disappear.

During the early to mid-1970s, several different technologies were used to print IC patterns on silicon semiconductor wafers. These included, at first, contact printing, where the mask was directly pressed against a wafer coated with a thin film of photosensitive polymer, so that a high-quality image could be transferred during exposure to ultraviolet light. However, this technique was inherently defect-prone and greatly limited the yield of good integrated circuits on each wafer. It was quickly replaced by the basic concept of physically separating the mask from the surface of the wafer.

Initially, a proximity technique was used, where the mask and wafer were separated by a small gap. This gap was intended to reduce the defect density, but this procedure had an inherent problem. If the mask and wafer were separated by more than a critical distance (dependent upon the feature size on the mask and the wavelength of the exposing light), then the pattern fidelity was lost due to optical diffraction effects.

Consequently, proximity printing lasted only a few years and was replaced by a reflective, unity magnification, optical image projection system. This technique became very popular, since it produced high-quality images with smaller feature sizes and greatly improved circuit yield per wafer. Integrated circuit technology quickly entered into the era of large-scale integration.

However, the lithographic technical community was struggling with the many issues associated with optical lithography, and researchers began to look for other lithographic techniques. In the early 1970s, many researchers began to investigate a new technology, X-ray lithography. Using the proximity mode of pattern replication and X rays with wavelengths ranging from 5-15 Angstroms, diffraction effects were essentially eliminated for the then-current design rules of approximately 5.0 μm. Much work had to be accomplished if X-ray lithography was to quickly replace optical lithography. This included the development of X-ray-sensitive resist polymers, appropriate mask structures, and X-ray sources that met the requirements of wavelength and brightness.

However, in the late 1970s a second-generation optical lithography technique quickly replaced the 1-to-1 projection system. The step-and-repeat camera that had been previously used to make masks was applied directly to wafer fabrication. This type of printing system allowed optical reduction of the master mask. With competitive wafer printing times and costs, this technique provided the semiconductor industry with a *defect-free* semiconductor lithography system.

But there appeared to be limits associated with the use of optical step-and-repeat systems. From an engineering standpoint, the quality of complex reduction lenses seemed to limit the technique, and mechanical issues associated with the precision movement of the wafer holder (stage) were extremely difficult. Nevertheless, evolutionary engineering improvements to optical steppers continued during the 1980s, and optical step-and-repeat systems dominated modern mass production semiconductor IC lithography.

However, researchers soon had to confront the fundamental physical limits of standard optical lithography. First, the wavelength of the exposing light was reduced into the deep ultraviolet region, using both mercury (Hg) light sources and krypton fluoride lasers (wavelength approx. 0.25 μm); and second, high-quality, pure, fused silica lens material and improved mirror systems were developed.

It appeared that ultraviolet optical lithography would be limited to minimum feature sizes of approximately 0.40 μm for manufacturing applications. The limitation would be due to the fact that diffraction-limited imaging systems would possess a depth of focus equal to or less than 1.0 μm. This is the practical lower limit for manufacture, considering such effects as wafer flatness and surface topology.

Recently, researchers have developed a new masking technology, called phase-shifted masks. The concept changes the mask structure from a simple clear-opaque structure to one which contains regions of different optical path length. Such a structure has been shown to increase both resolution (i.e., smaller feature sizes) and image focus tolerance.

As of today, researchers foresee a limitation of approximately 0.25 μm for optical ultraviolet lithography.

Manufacturing and Cost Issues

A basic objective of the semiconductor IC industry is to reduce the cost per electronic operation by the introduction of new IC fabrication and manufacturing technologies. The continual evolution in lithography, in terms of both larger imaging technology and smaller minimum feature size, is directed towards the goal of cost reduction. If the cost per electronic operation will rise with the introduction of a proposed new imaging technology, then the new technology is no longer considered a potential manufacturing technique.

An example of this general strategy of manufacture is found in the lithographic technologies used to fabricate ICs in small quantities as compared with large quantities. In order to simplify the illustration, consider the incremental cost factors. Using standard optical lithography to fabricate a particular IC design, the master mask cost per exposure level is approximately $2,000. In the simplest complementary metal oxide semiconductor (CMOS) technology, consisting of approximately 10 mask levels, each new design incurs a $20,000 mask-tooling cost. This cost is amortized over the number of ICs manufactured.

If, for example, one million circuits are manufactured, the mask cost is 2 cents per circuit. However, if only one hundred circuits are made for system design studies or for special limited applications such as satellite or undersea cable telecommunications, then the mask cost is $200 per circuit. This very high cost for a small quantity of circuits has led to another lithographic approach, namely that mask-making technology is adapted directly to semiconductor wafer fabrication.

It is well known that several large electronics corporations, including IBM and Hitachi, have adapted electron-beam lithography for small-quantity prototyping and/or manufacturing of IC designs.

Another example of the cost sensitivity of IC manufacturing is found in the utilization of capital equipment. In order to be competitive, an IC manufacturer must fully utilize capital investment. The operation of exposure tools at only 50 percent will double the lithographic costs associated with large-volume designs and significantly increase production costs. Therefore, most manufacturers must efficiently use and add capital equipment only in the smallest units consistent with their business strategies.

Integrated Circuit Performance Issues

By improving the printing quality of semiconductor lithography systems, smaller feature sizes can be used in the design and fabrication of ICs. This leads to an additional major benefit. The circuit performance becomes faster, leading to the creation of faster electronic systems, most notably computers. Thus a second and equally important impetus for smaller lithographic features is driven by circuit and system performance needs in areas such as information transfer and processing systems.

X-RAY LITHOGRAPHY DEVELOPMENT

As mentioned earlier, X-ray lithography has been undergoing research and development since the mid-1970s, but due to the success of optical lithography, XRL has never been introduced into manufacturing. X-ray lithography R&D has not been completely terminated, but it has evolved significantly in character. The technology continues to offer a substantial potential benefit to large-volume, leading-edge IC manufacturers. At present, many researchers and organizations believe that X-ray lithography will succeed optical lithography at the 0.25 μm feature size. This belief is based upon the exponentially increasing costs and technical issues associated with optical lithography.

While initial research has been recently reported on projection XRL, all active research that could lead to XRL insertion into manufacture in the 1990s time frame is based on the principle of proximity imaging, used in a step-and-repeat mode. The mask and the wafer are separated by a small gap that allows for high-fidelity imaging while eliminating the defects caused by contact printing. Typical parameters for present R&D systems areas are as follows:

wavelength	= 10-15 Angstroms
mask/wafer gap	= 20 μm (typical)
feature size	= 0.25-0.50 μm

A most critical parameter in any lithographic system is the exposure time, because it determines the manufacturing throughput and the associated cost. Initial efforts in XRL attempted to use stationary or rotating electron bombardment X-ray generators, but researchers were unable to develop resist systems that had the associated sensitivity required for high-throughput manufacturing. As a result, major efforts were directed towards identifying a high-brightness X-ray source.

The internationally accepted solution to this source problem has been the electron synchrotron. The synchrotron X-ray source is based upon the phenomenon that when electrons are moving at relativistic speeds and are accelerated in a circular motion, they emit very large quantities of X rays.

There is, however, a major issue with the use of synchrotron X-ray sources. They are of such a nature that to be used economically in X-ray lithography, a synchrotron-based lithographic system must contain at least eight to twelve beamlines. This implies that IC manufacturers will have to add lithographic capability to their manufacturing lines in rather large units. Manufacturers are now contemplating the construction of new IC production lines that will have the ability to house a synchrotron. This is a major issue, since it implies that radiation shielding and a facility floor plan required by the synchrotron system must be carefully considered at the outset of the production line design. Furthermore, such a facility tends to be directed towards the manufacture of large-volume, leading-edge commodity ICs such as dynamic random access memories (DRAMS) and static random access memories (SRAMS).

Considering this issue, other X-ray sources are being investigated on a small scale, including free-electron lasers (particularly in the United States), plasma sources, and laser ablation techniques, but the synchrotron has dominated the efforts of the international technical community for at least the past seven years. In particular, the governments of Japan, Germany, and the United States have all sponsored, to various degrees, R&D in the field of proximity synchrotron XRL.

The national program of Germany, conducted at the Fraunhofer Institute, encountered major technical problems with the synchrotron source, and as a result, most of the research has been significantly reduced. Within the industrial sector of Germany, there are no known proximity synchrotron XRL programs being actively pursued.

In the United States, a program sponsored by agencies within the Federal Government is addressing various segments of the technology; but to date, a complete, funded plan for total systems integration and demonstration is still being formulated. In the industrial sector, only the IBM Corporation has developed a complete plan and is presently installing a superconducting synchrotron in its new facility at Hopewell Junction, New York.

X-RAY LITHOGRAPHY RESEARCH AND DEVELOPMENT IN JAPAN

In Japan, the XRL R&D effort is very extensive, consisting of the following:

a) Government support of national research institutes
b) A government/industry consortium, called SORTEC
c) A comprehensive program by the telecommunication giant, NTT
d) A wide variety of R&D efforts wholly within the industrial sector

National Research Institutes

The Japanese government has two efforts directed towards various academic and industrial research projects associated with synchrotrons.

The first effort is located at the high-energy research laboratory, KEK, located in Tsukuba. This laboratory receives approximately $20 million a year in funding from the Ministry of Education.[1] At this synchrotron facility, there are four independent industrial efforts engaged in the use of the synchrotron to study XRL. The organizations doing active research are NTT, Hitachi, NEC, and Fujitsu.

The second national effort is centered at the Electrotechnical Laboratory (ETL), which is also located in Tsukuba. This laboratory is involved in many different areas of electronics research. It is funded by the Ministry of International Trade and Industry (MITI), with an annual budget of approximately $70 million. At this laboratory, a small effort in XRL has been conducted over the past several years, but presently it is being transferred to the SORTEC consortium. The major effort at ETL is in the design and characterization of synchrotrons. Working with Sumitomo Electric Corporation, ETL has constructed and evaluated four synchrotrons, named the NIJI series, including one superconducting type.

SORTEC Consortium

SORTEC is an industry/government MITI consortium specifically created to investigate the technology of proximity synchrotron XRL. There are fourteen organizations actively involved:

The Japan Key Technology Center
Toshiba Corporation
NEC Corporation
Hitachi, Ltd.
Fujitsu, Ltd.
Matsushita Electric Co., Ltd.
Mitsubishi Electric Corporation
Oki Electric Industry Co., Ltd.
Sanyo Electric Co., Ltd.
Sharp Corporation
Sumitomo Electric Industries, Ltd.
Sony Corporation
Canon Inc.
Nikon Corporation

The consortium was founded in 1986 and funded with a total sum of $100 million. The original plan calls for a ten-year life cycle. Seventy percent of the funding was supplied by MITI and the remaining 30 percent by the participating industrial organizations. The consortium has established a completely integrated lithographic system based upon a non-superconducting synchrotron design; experiments are

1 Information and statistics presented in this section are based on a compendium of brochures and oral briefings given to the panel by our Japanese hosts at the various sites visited. See Appendix E for further details.

currently being conducted by the SORTEC employees and the various member corporations. In its four years of existence, SORTEC has performed a remarkable job. (See Appendix E, "Site Visit Reports" for a detailed description of the technical activities at SORTEC.)

The NTT Proximity Synchrotron XRL Program

The leading effort in Japan in the R&D of XRL is clearly the Nippon Telephone and Telegraph (NTT) project. The synchrotron project was started in the mid-1980s, and a comprehensive plan was devised to develop all aspects of the technology. A completely new laboratory including clean rooms was specially constructed for this project. Room-temperature and superconducting synchrotrons have been designed, constructed, installed, and are presently running. Beamlines and aligners are also in place.

For potential XRL mask making, high-resolution electron beam machine design and prototyping were contracted to Hitachi. A silicon nitride membrane mask technology was developed and refined. NTT is now fabricating devices within its facility. Its R&D efforts have been generally successful and are the most advanced in existence.

NTT is a corporation that is owned 70 percent by the Japanese government and 30 percent by the public. It is also a government monopoly with respect to public telecommunications. By law, it is forbidden to manufacture telecommunications products; therefore, it licenses its developed technologies to contractors. NTT also licenses the results of its R&D to private firms on an international basis.

The Independent Industrial Sector Activities

The Japanese government is actively involved in the XRL R&D efforts, but the panel's on-site studies clearly demonstrated that the major portion of the R&D activities being conducted in Japan are led and financed by industry.

In one sector, the synchrotron development activities were well funded and actively pursued by several corporations, including Mitsubishi, Sumitomo Electric, Sumitomo Heavy Industries, and Ishikawajima-Harima Heavy Industries.

In a second sector, mask vendors and resist material suppliers had programs underway to supply the required materials whenever the technology was inserted into advanced development and manufacturing.

In a third sector, wafer alignment tools were viewed as engineering projects and could be supplied within one- to two-year time periods. The Canon Corporation was in the process of building two prototype aligners during the panel's visit.

In a fourth sector, all major IC manufacturers had active programs in XRL R&D. The level of activity varied from corporation to corporation, but each organization seriously considered XRL as a possible manufacturing technology. The overall impression was that optical lithography would continue to dominate manufacturing for the next 5 to 7 years and, consequently, the XRL programs were paced accordingly.

SIGNIFICANT FINDINGS OF THIS REPORT

The following chapters of this report detail the results of the JTEC panel's technical findings with respect to the many Japanese R&D XRL programs. Appendix E describes each on-site visit. The Executive Summary was developed from the most significant observations of the panel.

A concise summary of the panel's findings follows:

1. Lithographic research and development in Japan for microelectronics manufacture is based upon well-developed strategies and is well financed, primarily by the private sector.

2. Active research is being conducted in optical, electron-beam, and XRL lithography.

3. Optical lithography is viewed as being the dominant manufacturing lithography technology until the later part of the 1990s (about 1998), when 0.25 μm design rules will used for the manufacture of 256 megabit DRAMS.

4. The Japanese government has provided important "seed funding" for synchrotron-based proximity XRL R&D.

5. The synchrotron is the preferred source of X rays.

6. All major issues associated with X-ray lithography are being researched, including beamlines, masking technology, aligners, and resist materials.

7. From the standpoint of basic science, the United States and Japan are equally established in the fundamentals of XRL; however, the Japanese industrial sector is deeply involved in the development of this technology. Japanese industry will lead the world in establishing the success or failure of this technology to compete with alternate lithographic approaches to the manufacture of 0.25 μm ICs.

CHAPTER 2

X-RAY SOURCES

Franco Cerrina

INTRODUCTION

In Japan there is strong activity in the area of synchrotron radiation sources development; little is visible in the area of plasma and other X-ray sources. There is a general consensus in the Japanese industry that synchrotrons are needed for the application of X-ray lithography (XRL) to semiconductor manufacturing. Other sources of X rays are perceived as being either too weak or too undeveloped to warrant consideration at this stage. The accelerator technology is mature to the point that the production of electron storage rings must be seen as a manufacturing optimization problem rather than an R&D program. A possible exception may be in the area of superconducting systems, where several issues remain to be addressed; however, the successes obtained in Japan (three superconducting rings are operational) seem to indicate that no major obstacle exists in that area either. The race in the development of dedicated rings is thus not based on developing new technology, but rather on improving the performance/cost ratio of the machines.

In the construction of electron storage rings, Japanese organizations appear to be ahead of the United States. Several rings that are described below are already operational with exceptional performances (the SORTEC ring, for example). It also appears likely that the Japanese will be in the second or third generation of design before any of the new U.S. dedicated synchrotron sources will be operational.

In the United States, there are two initiatives that are dedicated to the construction of rings specifically designed for X-ray lithography. The first, at Brookhaven National Laboratories, is devoted to the design and construction of a prototype superconducting ring that is estimated to be at least two years from completion (1993). The second, a room-temperature ring built by Maxwell-Brobeck for Louisiana State University, is scheduled for completion in 1992. Thus, it appears that construction of industrial accelerators and storage rings will be dominated by the Japanese. The only other competitor outside of the United States appears to be Oxford Instruments, a British firm that has designed and commissioned a superconducting ring was delivered to IBM in March 1991.

This chapter will briefly describe the activity ongoing at the various sites in Japan and provide more detailed technical information on the various rings. The site reports in Appendix E contain some relevant formulae and more detailed material that has been included to facilitate comparisons.

THE DEVELOPMENT OF THE SYNCHROTRON ORBITAL RING IN JAPAN

JTEC teams visited seven locations where the development of a synchrotron orbital ring (SOR) is being pursued. The design parameters and performances achieved are summarized in Table 2.1.

The development of SORs for X-ray lithography rests on a very well understood technology. Synchrotrons and electron storage rings have been in use for decades; the main challenge lies in the development of cost-effective sources. Staff at all the sites the panel visited displayed an excellent understanding of the physics of electron accelerators and an interesting variety of approaches to the common problem of building a production-worthy SOR.

Photon Factory

The Photon Factory is the principal multipurpose synchrotron radiation facility in Japan. Comparable facilities in the United States are the National Synchrotron Light Source at the Brookhaven National Laboratory, Stanford Synchrotron Radiation Laboratory, and the University of Wisconsin Aladdin. Japan's Ministry of Education provides $20 million annually for operation (exclusive of scientists' salaries). The facility provides to users 3500 hours of light per year. Although the ring can hardly be considered dedicated to X-ray lithography, it has played a key role in providing a focal point for initial X-ray lithography development.

Four major Japanese companies have lithography beamlines at the Photon Factory (on the indicated beamlines): NTT, Hitachi (B.L.8), NEC (B.L.9), and Fujitsu (B.L.17). These companies pay $400/hour for photons. They must provide their lines to general users for half of the available beam time. Tours were provided to the panel by Hitachi and NTT.

In general, the lithography work seen at the Photon Factory is research on important aspects of the overall lithography problem, largely beamline design, masks, and resists. (NTT is also performing measurements on optics for

Table 2.1

Japanese SOR Overview												
Location			Photon Factory	ETL	ETL SUMITOMO E	SORTEC	NTT	NTT	MITSUBISHI Electric Ind.	SUMITOMO Heavy Ind.	IHI	
Name			KEK	TERAS	NIJI-III		Super-ALIS	NAR	HEBRF	AURORA	Luna	
Design												
	Energy	GeV	2.5	0.8	0.62	1	0.6	0.8	0.8	0.65	0.8	GeV
	Gamma		4892.5	1565.6	1213.34	1957	1174.2	1565.6	1565.6	1272.05	1565.6	
	Bending Radius	Meters	8.33	2	0.5	2.78	0.66	1.83	0.59	0.5	1.96	Meters
	Magnetic Field	Tesla	1.00	1.33	4.13	1.20	3.03	1.46	4.50	4.33	1.36	Tesla
	Magnets	Temperature	RT	RT	SC	RT	SC	RT	SC	SC	RT	Type
	Critical Energy	keV	4.09	0.56	1.04	0.78	0.71	0.61	1.89	1.20	0.57	keV
	Current	mA	xx	250	250	200	250	20	xx	300	50	mA
	Lifetime	hours	xx	4h	2-3h	4h	4h	xxx	xx	24h	6h	hours
	Injector	type	Linac	Linac	Linac	Linac	Linac	Linac/SOR	1 GeV Synch.	Microtron	Linac	type
	Injection Energy	GeV	2.5	0.33	0.33	0.04	0.015/0.8	0.02	0.8	0.15	0.05	GeV
	Injection time	minutes	xx	xx	20'	1'/top-off	10-20'	xxx	xx	few minutes		minutes
Status												
	Ring		oper.	oper.	oper.	oper.	Oper.	oper.	development	oper.	oper.	
	Energy Achieved		full	full	full	full	full	full	xx	full	full	
	Current	mA	300	250	120	250	150	>20mA	xx	300	15	mA
	Lifetime	hours		8h	8h	13h@250mA	4h@100mA	2h	xx	6h@100mA	1h@15mA	hours
	Beamlines	number	40+	6	none	2		4				number
Constructors				MEI, MS	SEI	MEI, T	H, MEI	MEI	MEI	SHI	IHI	

projection X-ray lithography.) Despite its industrial importance, the work has a clear academic flavor. None of the companies' beamlines has a stepper, and no functional integrated circuits have been made with X-ray lithography at the Photon Factory.

Electrotechnical Laboratory, Quantum Radiation Division

The goal of the Electrotechnical Laboratory (ETL) Quantum Radiation Division (QRD) is that of constructing the accelerators needed by the Electrotechnical Laboratory itself. The laboratory houses all the sources that have been built by the division. It is on two floors: the first is above ground and houses the management room and the measurement control room; the rest of the building is underground so that all the X-ray sources are naturally shielded.

A key part of the facility is the LINAC, which is capable of accelerating to about 300 MeV and serves as the main injector for the various rings that have been built at the center. The magnets for the LINAC were built by Mitsubishi Steel, and the quadruples are supplied by Mitsubishi Electric. There are four electron storage rings operational at ETL QRD as of November 1990: TERAS (Tsukuba Electron Ring for Accelerating and Storage) and NIJI-I, -II and -III (Niji means rainbow in Japanese). NIJI-I was a prototype built in 1988 for the study of low-level injection; it was disassembled and replaced by NIJI-II. Each ring is housed in its own laboratory. Table 2.2 lists the properties of the five rings; these are discussed in some detail in the following sections.

Table 2.2
Properties of ETL's Electron Storage Rings

	Type[a]	Energy (GeV)	Current (mA)	Applic	E_c (eV)	Size (μm)	Status
TERAS	RT	0.8	250	Gen	568	10	Up
NIJI-I	RT	0.27	524	Exp	62	4	Off
NIJI-II	RT	0.6	120	Exp	342	4x6	Up
NIJI-III	SC	0.62	120	XRL	1057	4x5	Up
NIJI-IV	RT	0.5	-	FEL	231	4x12	Cnstr

[a] RT = room temperature; SC = superconducting

The QRD has an impressive array of machine-building skills, and the Director, Dr. Tomimasu is certainly a world figure in this arena. He and his staff have developed a large reserve of know-how (and parts!) so that they can easily design and assemble a new accelerator in a short period of time and at little cost. The United States is lacking a comparable facility.

TERAS. The TERAS ring is the workhorse of the QRD facility. First-beam storage was achieved in 1981, and the storage ring has been operating ever since for various applications, including photoelectron spectroscopy, radiometric standards, photo-irradiation studies, solid-state physics, and in particular, X-ray lithography studies. TERAS is fairly similar to some of the U.S. rings (the VUV ring at Brookhaven and Aladdin in Wisconsin). The ring is an accelerating type, since the electrons are injected on the LINAC at 300 MeV and then are further accelerated to the operational energy of 800 MeV. Maximum current stored in the ring is on the order of 250 mA with a lifetime of several hours. The ring structure is four-fold symmetric with 8 bending magnets and 4 triplets for beam focusing. It is interesting to note that the ring at ETL was designed in a year and assembled in about 10 months for a total cost of ¥250 million.

The ring appears to be a well-designed and well-implemented system, but with characteristics appropriate to a research and development facility; that is, the efforts have clearly been concentrated on developing a working ring in the fastest time and at the lowest possible cost, rather that on developing a product suitable for commercialization. The transfer of technology to a manufacturer's production model would require considerable engineering of the design. The operation of the ring has been very successful with very high up-time and excellent performance.

Of particular interest to the panel was the beamline implemented for X-ray lithography studies, because it contains an *electron* beam scanning system. In X-ray lithography, it is necessary to spread the horizontal fan of radiation onto the whole field of exposure, typically on the order of 30 mm vertical by 25+ mm horizontal. This can be achieved in several ways: rastering mask and wafer together across the beam; scanning the beam by using an optical mirror; or oscillating the electron beam. ETL chose to implement the electron beam scanning system. When an electron is accelerated in a magnet field, the radiation is emitted in the plane defined by the orbit of the electron. If this plane is oscillated, the radiation will follow the movement of the orbit plane, producing an oscillating fan of radiation at the sample position. (This is analogous to oscillating a flashlight in order to spread its beam on a vertical length.) The method was successfully implemented at TERAS for the X-ray lithography beamline. There are several advantages to this method since it does not require the use of any optical or mechanical system to spread the radiation. However, it is difficult to use such a method in a system shared by many users because of the perturbations on the orbit that are created by the (localized) oscillation of the beam.

NIJI-I / NIJI-II. It is important to note that the NIJI series was built in a collaboration between Sumitomo Electric and ETL. The NIJI-I and -II rings were built as prototypes for construction of the superconducting storage ring NIJI-III. The design study of NIJI-I began in 1984 and was completed in 1986. The ring was a small-size, conventional magnet, electron storage system and was intended to study the injection into low-energy machines. NIJI-I was able to store up to 500 mA of 160 MeV electrons with a lifetime of about 70 minutes. These data are very important because they demonstrate the possibility of storing a large amount of current at low energy, i.e., the possibility of low-energy injection. The ring was shut down and disassembled in March 1989. It was replaced by NIJI-II as a prototype for the construction of the superconducting ring. The maximum current stored in NIJI-II was 120 mA, and the study is considered completed at this time. Two undulators are installed on NIJI-II, one for CVD experiments and the other for elliptical radiation sources. No beamlines are installed on this ring.

NIJI-III. NIJI-III is a relatively compact superconducting storage ring, as shown in Figure 2.1. It has a cold bore (i.e., the walls of the vacuum chamber within the bending magnets are kept to liquid helium temperature) and can oscillate the beam in order to define a large exposure area, as discussed above. The ring is operational, and after the initial period of studies, it will be shipped to the Sumitomo Electric plant where it will be outfitted with a beamline and used for X-ray lithography applications. Dr. Tomimasu expected this to happen in the early part of 1991. Dr. Tomimasu commented that a leak did cause a long down time because of the cold walls. The machine can be injected quickly, and it then accelerates the electrons to the operating energy. It takes about 20 minutes for an injection cycle. The lifetime is several hours. The design of this superconducting storage ring is different from the usual ones based on a racetrack design.

NIJI-IV. This is a long-straight section ring designed to incorporate a free-electron laser (FEL). It was under assembly and is expected to be operational in 1991. The applications are for basic research and spectroscopy.

SORTEC

SORTEC was established in 1986 with a $100 million budget for a 10-year plan. The fund was established in part by MITI (through the Japan Key Technology Center) and by the 13 other member organizations[1]:

---

[1] The Japan Key Technology Center is considered to be a member of SORTEC. The thirteen other members are private companies bringing the total membership to fourteen.

The Japan Key Technology Center
Toshiba Corporation
NEC Corporation
Hitachi, Ltd.
Fujitsu, Ltd.
Matsushita Electric Industrial Co., Ltd.
Mitsubishi Electric Corporation
Oki Electric Ind. Co.
Sanyo Electric Co.
Sharp Corporation
Sumitomo Electric Ind.
Sony Corporation
Canon, Inc.
Nikon, Inc.

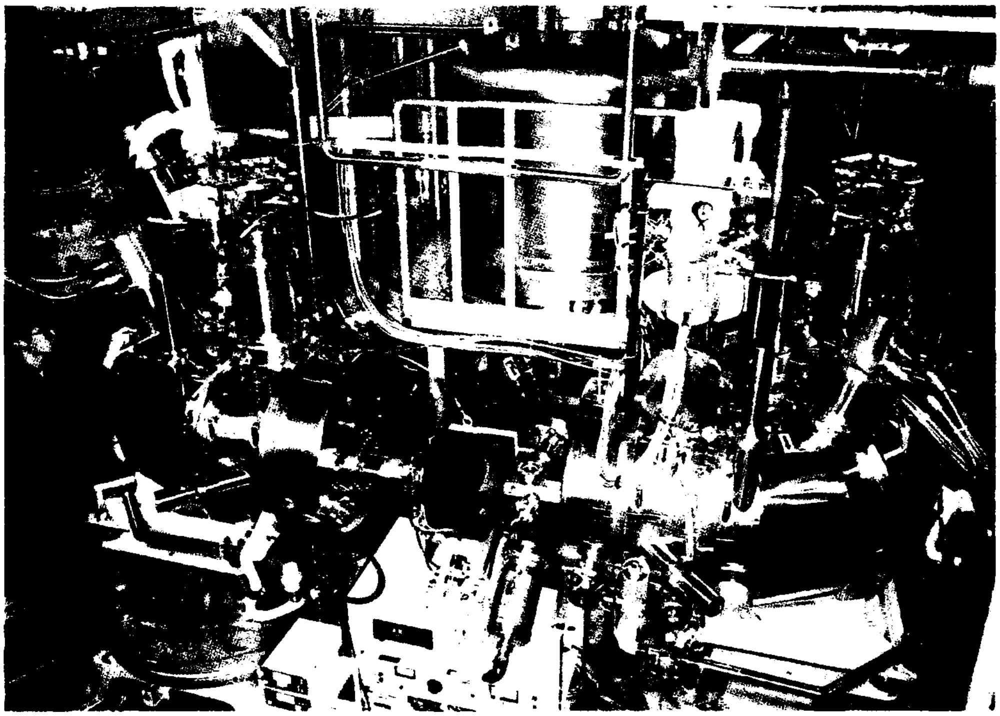
The SORTEC plan requires development of three items: source, beamline, and stepper. Dr. Atoda summarized the status of the ring: 200 mA at 1 GeV, with 13 hour lifetime at 200 mA. These results are excellent. They become even more impressive considering it took SORTEC *less than 4 years* to complete the rings.

The SORTEC rings are a beautiful example of the combination of accelerator physics and excellent engineering. It is important to note the careful planning and early studies that led to this success. For example, the exceptionally long lifetime was made possible by careful study of the outgassing of the stainless steel exposed to SOR.

Dr. Okada specified that Toshiba built the booster synchrotron and Mitsubishi Electric built the LINAC and the electron storage ring. The SORTEC staff consists of 34 employees, of whom more than 20 are researchers with a rotation period of 2-3 years. The facility includes the following:

a) *Control room.* It is well organized and cleanly laid out. All the standard systems were in place (beam monitors, current recording, etc.). The panel was told by Dr. N. Awaji (Chief Researcher, SOR) that the ring is quite flexible and that the beam emittance is controlled in the limits of 0.1-5 mm-mrad, 0.5 being a typical value. The ring can work now in top-off mode, thus keeping the current constant to within one percent. It has a vivid graphic display of the ring and beamline status.

b) *Rings.* There are 3 subsystems: injector (built by Mitsubishi Electric Industries); booster synchrotron (built by Toshiba); and storage ring (built by Mitsubishi EI). Figure 2.2 shows the layout of the rings. All the facilities



This ring is now being developed under commission from the Research and Development Corporation of Japan in order to achieve practical application of the electron undulating method successfully developed by the Agency of Industrial Science and Technology, and it is based on SEI's original superconducting technology. The use of a superconducting coil results in a more compact size (ring dimensions of approximately 3 × 5 m) and also makes possible the release of synchrotron radiation having a spectrum ideally suited to x-ray lithography.

Energy	: 615 MeV
Bending radius	: 0.5 m
Bending magnet	: Superconducting type
Circumference	: 15.54 m
Stored current	: 200 mA (designed)
Expected completion	: February 1991

Figure 2.1. ETL-Sumitomo Electric NIJI-III Ring

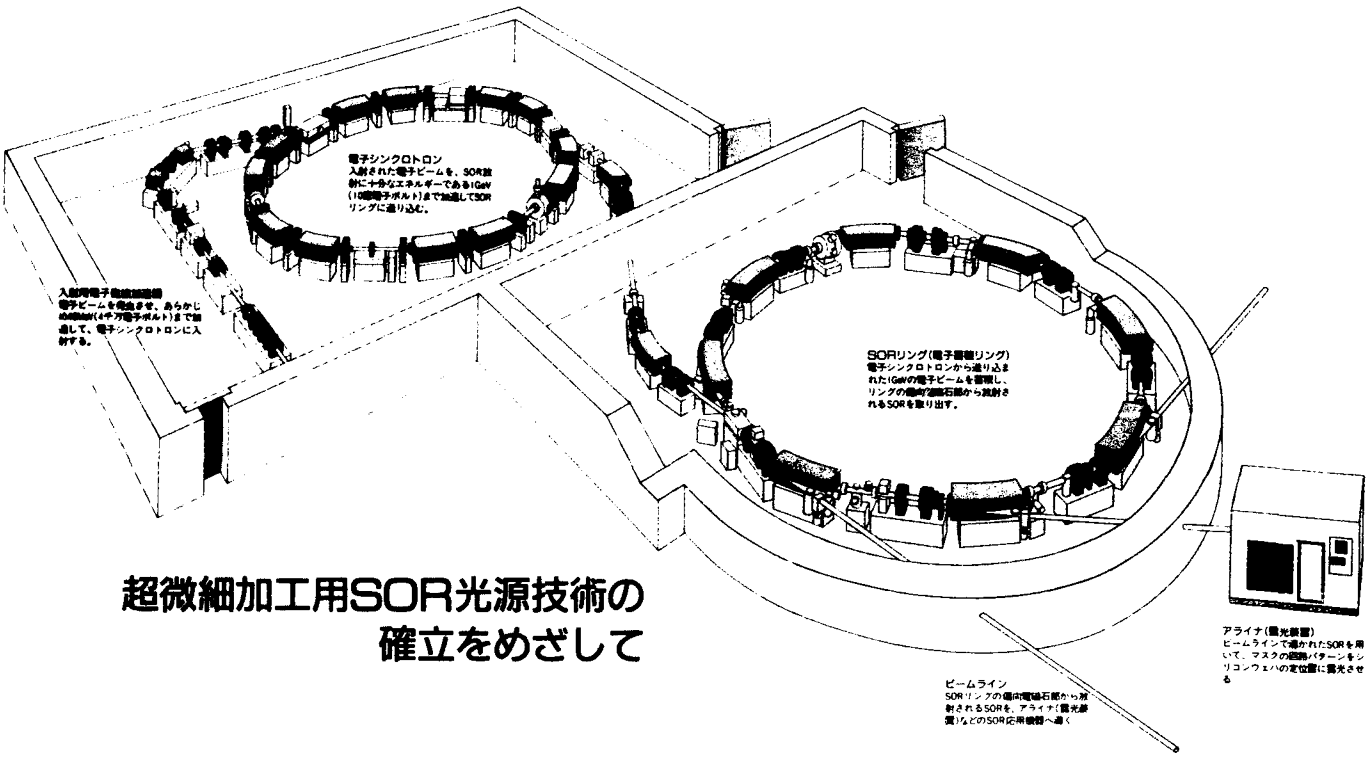


Figure 2.2. SORTEC Ring Layout

are in a spacious building extending two floors underground. The injector is a short 40-MeV LINAC that injects in the 1-GeV booster synchrotron. The design appears clean and well-implemented, with good equipment but without unnecessary frills. The booster synchrotron (Fig. 2.3) was similarly well-assembled. The magnets are standard Fe-Si layered construction, with the vacuum tank being a thin-walled stainless steel corrugated pipe (to reduce the eddy currents). A transport line connects the synchrotron to the SOR. Shielding around the synchrotron appears light, probably because of nonoccupancy during normal operation. The ring itself (Fig. 2.4) elicits the same comments; electronics are neatly packaged at the center of the ring.

In summary, the laboratory is well set up and managed. Performance of the rings is superb. Ring design and construction are clearly completed. Now SORTEC will turn its attention to process issues, including beamline and alignment systems. The SORTEC team is very strong, and it will go a long way in developing X-ray lithography.

Nippon Telegraph and Telephone

Nippon Telegraph and Telephone (NTT) has the oldest X-ray lithography program in Japan, dating from 1974. It has studied diverse sources, including X-ray tubes, plasmas, and storage rings. Its current program is very broad, including development and employment of a warm magnet storage ring, purchase and use of a superconducting magnet storage ring, development of two research X-ray steppers, and use of a full-fabrication line devoted exclusively to mask making.

The synchrotron radiation laboratories include a 15-MeV LINAC that can feed either the 800-MeV NAR (normal accelerating ring machine) or the 600-MeV Super-ALIS (superconducting Atsugi lithography SOR). Further, the latter machine can be injected with 600 MeV electrons from the warm ring. The main purposes of the rings are performing lithography development and studying different types of injection mechanisms. It is for this reason that Super-ALIS can be injected from either NAR (that then acts as a booster) or the LINAC.

NAR. The NAR ring includes two straight sections for future electron insertion devices. The current is now 20 mA with a two-hour lifetime. Currently it has four beamlines: one for X-ray lithography, two for characterization of X-ray optics, and one for surface science. A Class-1000 clean chamber with the initial stepper is fed by the X-ray lithography beamline. That beamline has a two-mirror optical system, the first of which is stationary to provide horizontal collimation, and the second of which oscillates vertically to sweep an exposure field. The exposure fields with

Figure 2.3. Booster Synchrotron

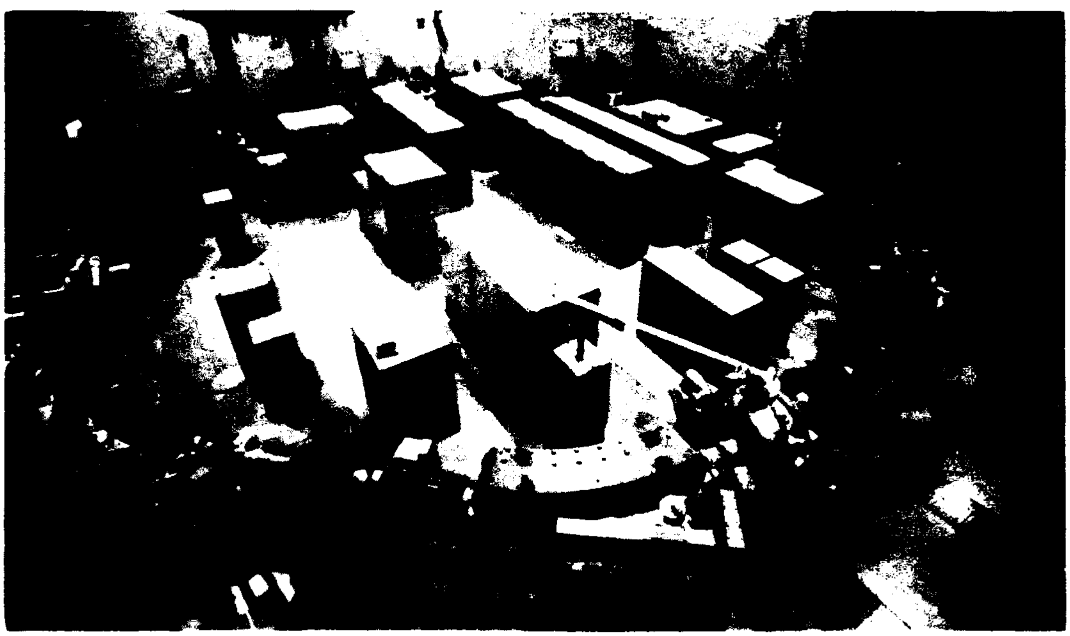


Figure 2.4. SORTEC SOR

the existing two-mirror beamline can be varied from 10 x 10 mm^2 to 20 x 20 mm^2. A second lithography line is under construction for use by Fujitsu, with the prospect that a third lithography line will be installed later for Toshiba.

Super-ALIS. The superconducting ring (Fig. 2.5) was designed by NTT, which took two years, and constructed and integrated by Hitachi, which took one year. The first beam was stored in February 1989. Currently, Super-ALIS can store 150 mA with four-hour lifetime or 100 mA with five-hour lifetime. It has three beamlines, all for lithography. The primary problems with the superconducting ring are the helium refrigeration system and the low-energy injection, which is very sensitive to the LINAC performance and can sometimes take thirty minutes. Despite these problems, the superconducting ring is extremely impressive. It is the first cold magnet storage ring designed and constructed exclusively for lithography. The machine is shut down twice per year for routine maintenance. NTT has had no major unexpected failures in the first year. There have been small problems, but nothing beyond what is expected as the machine is brought to full performance (500 mA).

Our hosts at NTT cited the cost for the LINAC and two rings as $20 million, although the JTEC panel did not pursue exactly what else this included (for example, salaries). It clearly must have excluded the very large laboratory that was built specifically for the storage rings. The number of personnel working on the rings, steppers, beamlines, and mask development was cited as 21 people. Ground breaking for the building was in October 1985; the facility was completed in March 1988.

Mitsubishi Electric

Mitsubishi Electric Industries (not to be confused with Mitsubishi Steel Industries) is active in all the various types of lithography. For X-ray lithography it is committed to synchrotrons, which it sees as the only viable source for large-scale production. It is designing and constructing its own SOR system. The machine will be a superconducting ring of 0.8 GeV energy (4.5 Tesla), fed by a booster synchrotron and a low-energy LINAC. The work, begun in 1988, is very advanced. The LINAC was almost completed at the time of the panel's visit, and the booster synchrotron was operational. The general layout is shown in Figure 2.6. The synchrotron will be used to feed more than one superconducting ring. Mitsubishi Electric did acquire considerable expertise in ring design through the construction of the LINAC and SOR for SORTEC. All the construction and funding for these new systems is internal.

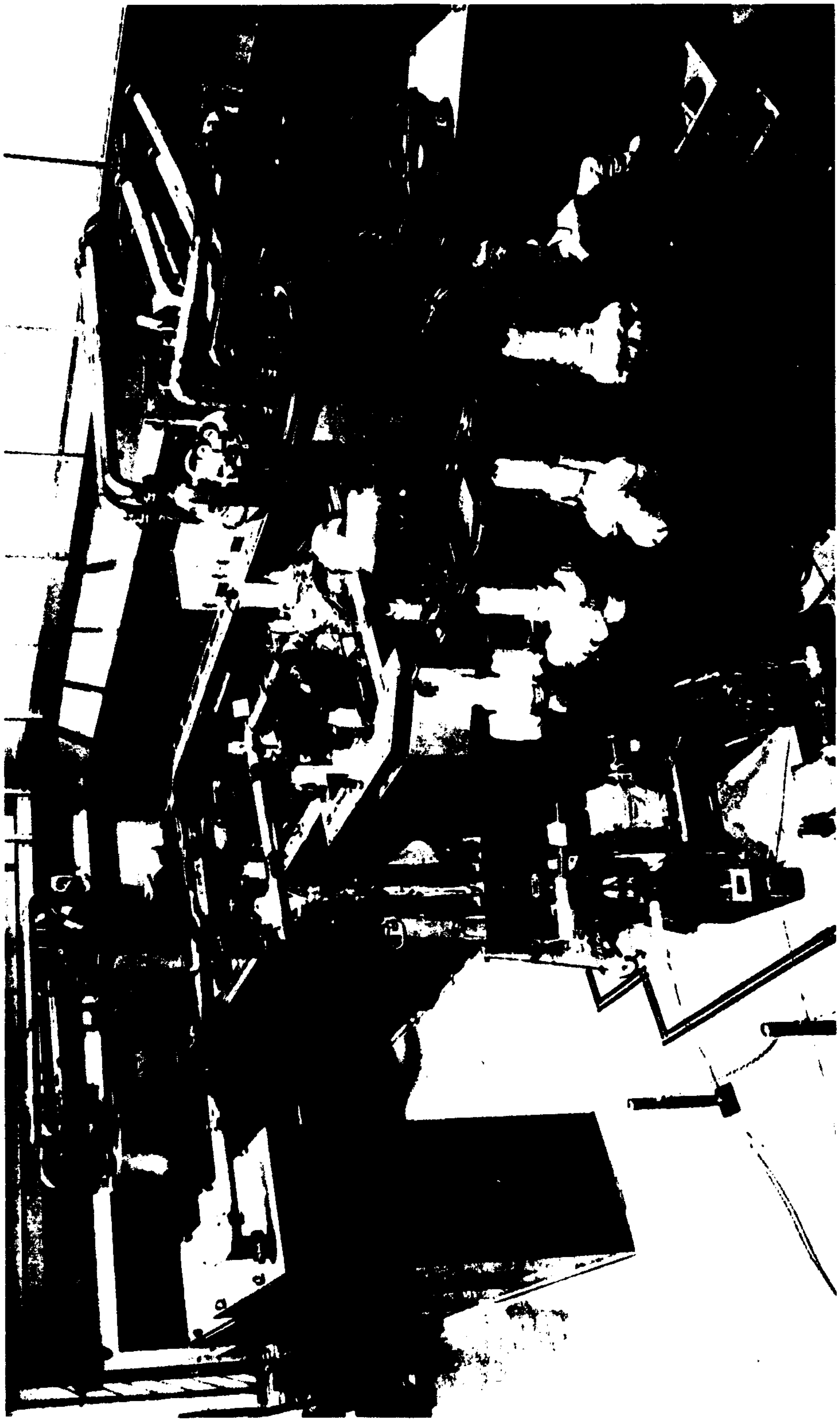


Figure 2.5. NTT Super-ALIS

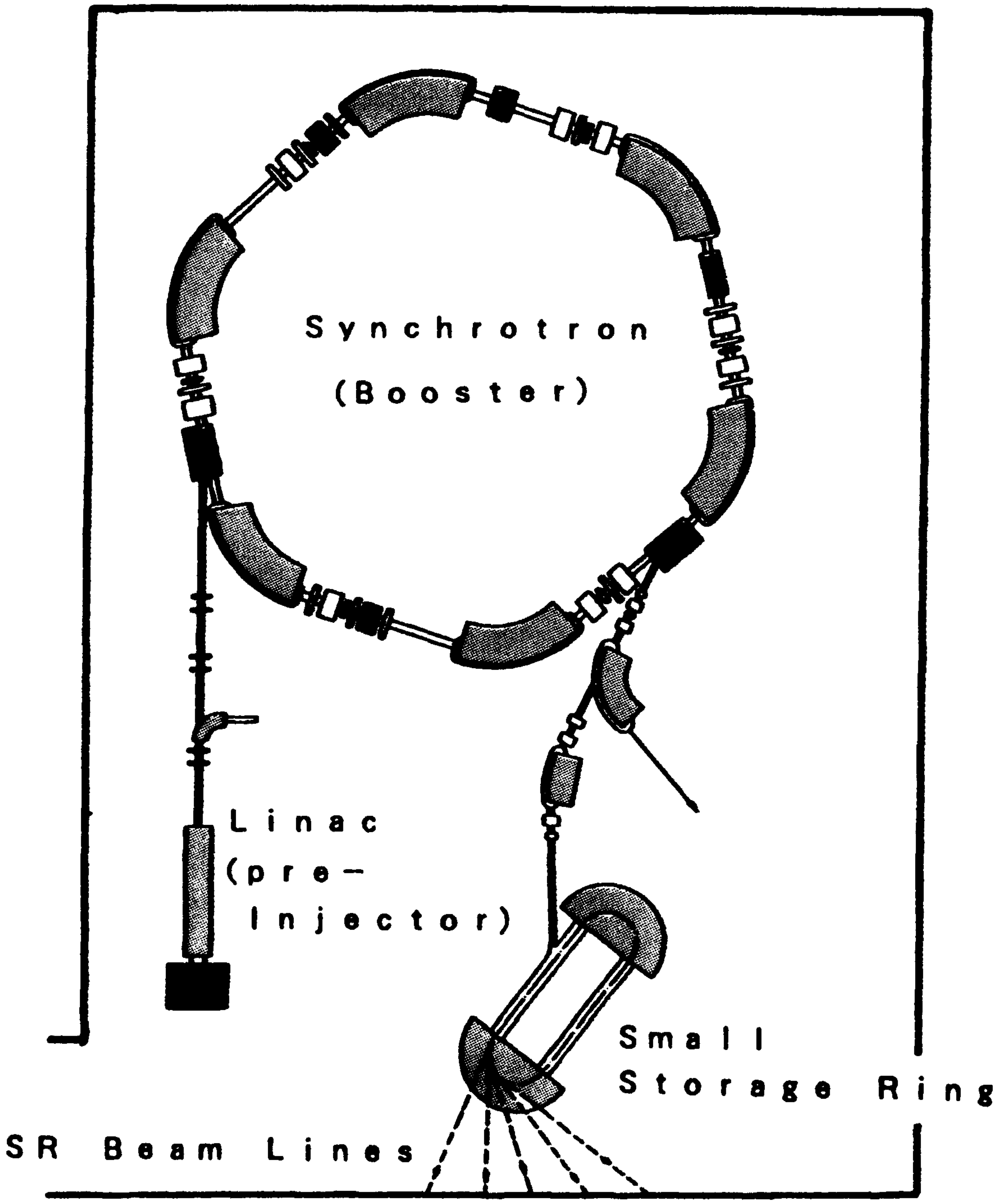


Figure 2.6. Mitsubishi Electric SOR Layout

Sumitomo Heavy Industries

Sumitomo Heavy Industries (SHI) may be the Japanese company closest to the goal of producing a truly marketable SOR. The design of its superconducting ring AURORA is unique, since it is based on a circular orbit, as shown in Figure 2.7.

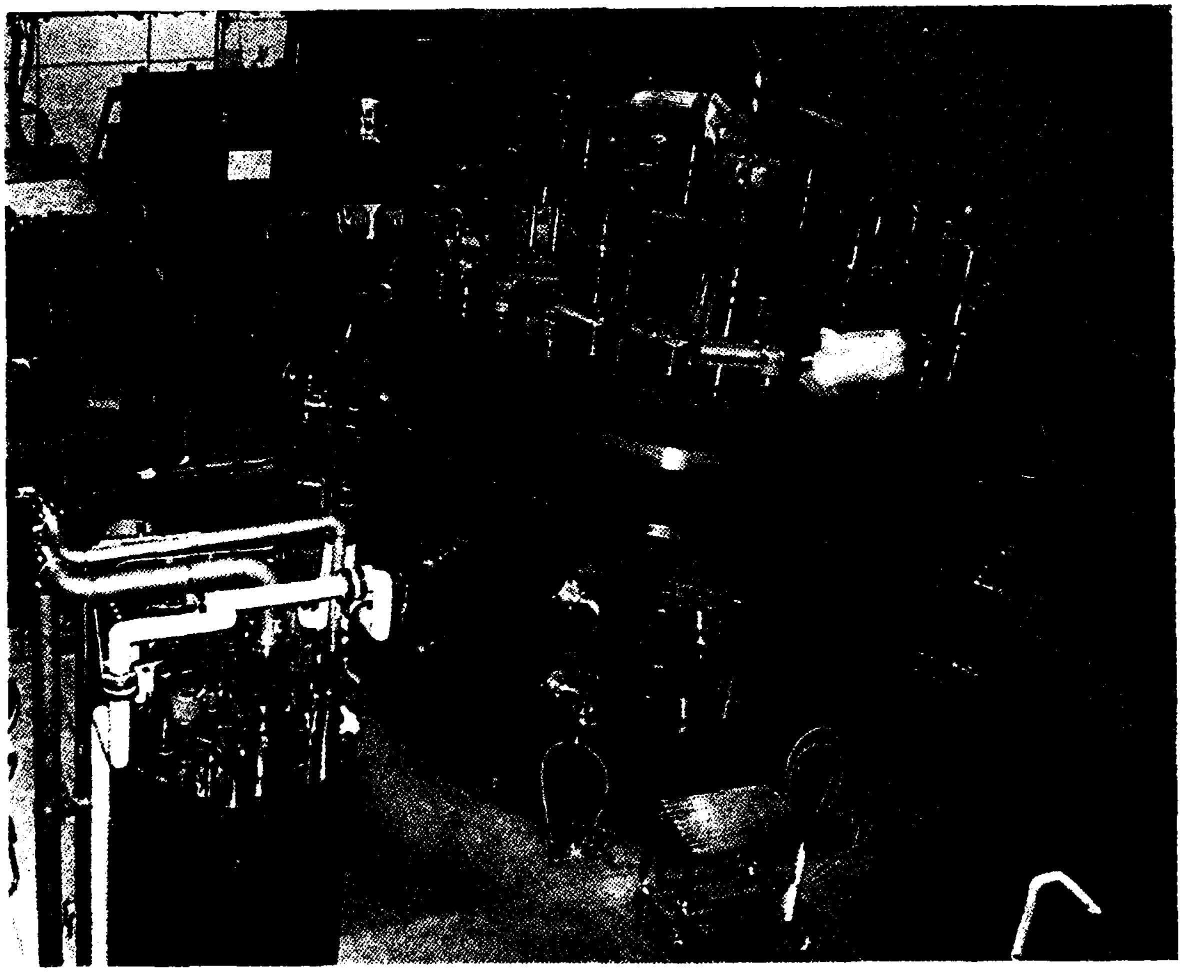


Figure 2.7. Sumitomo AURORA Ring

The magnets are based on a iron yoke weighing in excess of 100 tons. The heavy iron mass may help for shielding purposes. The machine also features a *warm-bore* design. The ring is injected by a low-energy microtron (150 MeV) and then ramped to full energy, each step taking only a few minutes. SHI has pioneered a novel injection mechanism based on the use of a racetrack microtron with 25 turns, an electrostatic inflector, and a magnetic perturbator. The scheme was adapted from the microtron of Aladdin, at the University of Wisconsin. The octupole field generated by the perturbator allows the capture of the injected beam in the stable orbit by the decay of the perturbing field. This approach generated considerable skepticism when first proposed, but it has been shown by SHI to be indeed workable and capable of producing excellent results. The system was just coming online at the time of the visit, so that the currents achieved can be considered quite remarkable--300 mA--but with a short lifetime (mainly attributed to outgassing). The situation is expected to improve as the vacuum walls are scrubbed by the radiation, as observed at other installations. It is interesting to note that there is a large pumping speed available by using He-cooled walls; this should allow a 24-hour pump-down time to 10^{-10} torr. The ring and the ancillary facilities appear to be very well designed, with a thoughtful degree of engineering in the implementation.

Layout of the ring and injector is shown in Figure 2.8. Helium consumption is estimated to be 10 liters/hour. The predicted cost of the system is around $20 million for the first units, with an expected decrease for further production. In late February 1991, it was announced that the ring had achieved 300 mA of stored current.

Ishikawajima-Harima Heavy Industries

Ishikawajima-Harima Heavy Industries (IHI) is building a prototype storage ring for lithography called LUNA (lithography-use new accelerator), which it hopes to sell for semiconductor production in the mid-1990s. This venerable company (established in 1853) does business of $6 billion/year; it is noteworthy for its large-scale products (e.g., shipbuilding) and its diversity (six major areas, including production of jet engines and space systems). The LUNA project grew out of IHI's welding capabilities that were extensively employed for the past dozen years to produce vacuum and other systems for high-energy physics. IHI did a preliminary design in 1987 for the 8-GeV synchrotron X-ray-radiation facility to be built in Harima by 1997.

The warm-magnet prototype LUNA was designed and constructed over the past two years (1989-91). Interestingly, IHI designed its own LINAC and RF systems. Ring assembly commenced in April 1989 and first beam in December 1989. LUNA has 45 MeV (LINAC) injection and 800 MeV operation. Current now is 15 mA

Main Specifications of AURORA

Injector

Type: Race Track Microtron

Energy	150 MeV
Energy Resolution	< 0.1%
Pulse Width	1.0 μsec
Peak Current	5 mA
Repetition Rate	10 Hz

Storage Ring

Type: Weak Focusing/Single Body

Energy	650 MeV
Stored Current	300 mA
Bending Radius	0.5 m
Critical Wavelength	1 nm
Magnetic Field	4.3 T

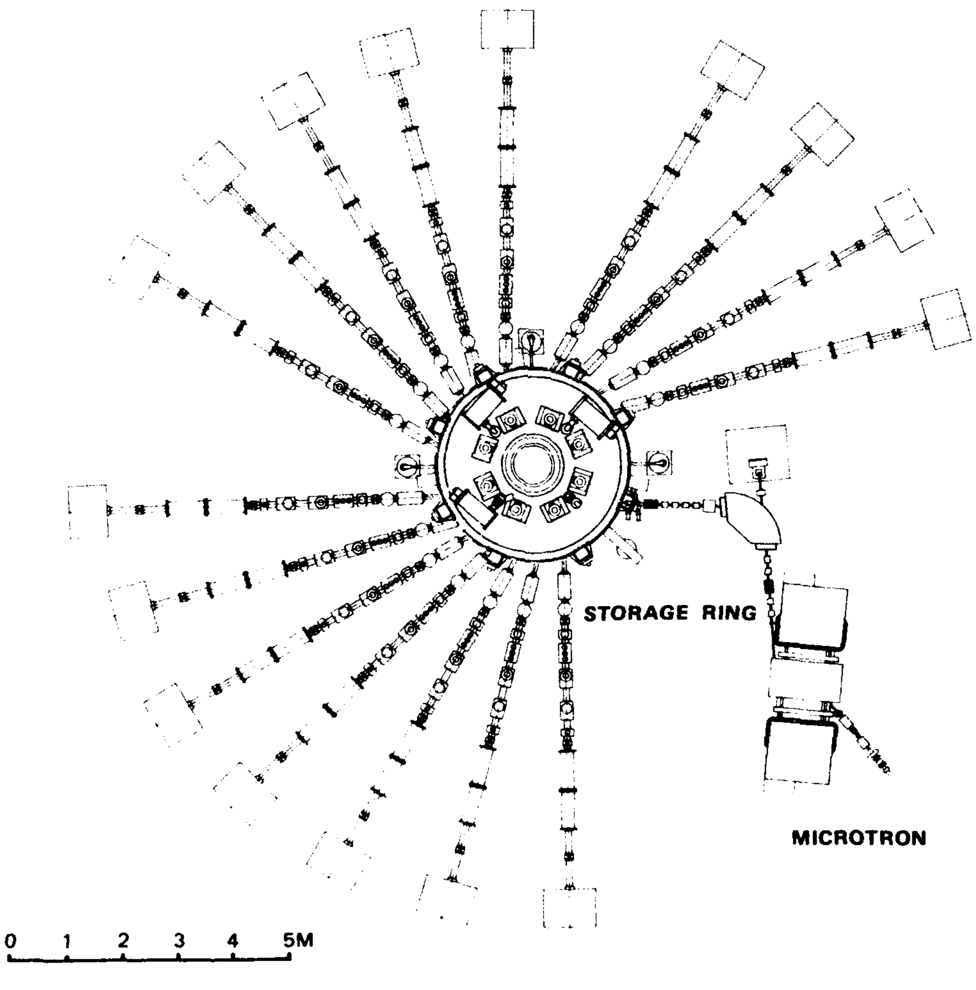


Figure 2.8. Sumitomo HI Ring Layout

(one-hour lifetime) with a goal of 50 mA. Full performance was expected in March 1991. Twenty people worked on the prototype, which cost $16 million. IHI believes semiconductor manufacturers will require ring costs below $8 million.

IHI touts the simplicity, reliability, and low cost of its ring as major advantages. The warm magnet design costs 60 percent of a cold magnet ring to build, although operating costs (electricity) will be higher for the warm ring. Size is a drawback. The major technical risk is low-energy injection (ramp time is only one minute). IHI does not now have a projection of how many ramp cycles will be needed to reach consistent and confident machine operation.

IHI expects to sell a production-design warm ring for integrated circuit R&D by 1996 or earlier. It would have LINAC injection from below, 5 ports mounted on each 90°-bend magnet (hence, up to 20 steppers), and (still) 50 mA. Two years will be needed from receipt of order to operation at the customer's site (including two-month assembly and six-month commissioning). IHI expects its ring(s) to be in use when mass production of integrated circuits by X-ray lithography begins in Japan in 1998 (256-Mbit DRAM).

IHI is also designing a cold ring, presumably to keep open its options. Overall, IHI has positioned itself (with no government involvement) to be a prime supplier of at least warm storage rings for X-ray lithography.

OTHER X-RAY SOURCES

The panel did not hear many descriptions of other types of X-ray sources. This could be attributed in part to the particular cross-section of the Japanese industry selected by the panel, and to the limited amount of time for discussion.

Free-Electron Lasers

Free-electron lasers (FELs) as a coherent source of X rays has been touted in the United States for applications to *projection X-ray lithography*, where the low reflectivity of the mask and optical system may require considerable input power. JTEC panelists did not find any indication of development of this type of source for XRL in Japan, probably because of the relatively low level of activity in projection XRL. FELs are of course being developed at several locations in Japan, including ETL, but primarily for basic research.

Plasma Sources

There is not much activity in the area of plasma sources for XRL, either. These sources are seen as being too weak and lacking the collimation of SOR sources for successful applications to mass production of semiconductor devices. Also, some concerns about reliability (i.e., lifetime of the laser's glass slabs) were expressed.

X-ray Tubes

This type of source is not seen as useful for X-ray lithography production applications at all, although Nikon used it on its XRS 5 system for research and development and demonstration purposes.

CONCLUSIONS

The status of the development of synchrotron-based X-ray sources in Japan is very advanced, to the point of qualifying the Japanese as leaders in this area. Japanese organizations have entered the engineering phase after a successful research and development stage. The excellent results achieved at SORTEC, ETL, NTT, and Sumitomo prove that the technology is well understood.

It is noteworthy that several industries have participated in the development of various components of the technology at other sites (Mitsubishi Electric is an excellent example) and are now applying the technology in their own internal projects. Furthermore, several of the large industries can rely on their internal strength and diversification for large engineering programs such as the construction of SOR exposure systems.

Japanese industries are aggressively moving into the manufacturing stage, and less expensive SORs are likely to be available on the market within a short time. The current cost of Japanese SORs is in the range of $20-25 million, but the panelists were told that cost is expected to drop to the $10 million range (and even below) as production starts and engineering costs are defrayed. The first generation of rings may be available on the market as soon as 1991 (Sumitomo Heavy Industries). It is not clear if other machines, such as those developed at SORTEC and operational now, will be commercialized. Their performances should make them strong contenders in the market.

CHAPTER 3

BEAMLINES AND ALIGNERS

Robert W. Hill

INTRODUCTION

The exposure system used with synchrotron based semiconductor lithography systems consists of beamlines to transfer X rays, and mechanical fixtures to hold patterned masks and semiconductor wafers coated with resist in the path or "field" of radiation. The mechanical systems for moving and holding the mask/semiconductor wafer combination are referred to as either "steppers" or "aligners". Aligners vary from relatively simple systems that expose one field at a time for research purposes to highly automated systems that rapidly unload wafers and masks from their holders or cassettes and that have very sophisticated alignment and control systems for positioning the mask with respect to the wafer. Some of these systems are capable of aligning and exposing multiple fields per wafer and can handle wafer sizes from 100-200 mm. Japanese manufacturers have started to work on the development of the elements of highly sophisticated manufacturing systems, although most of the installed systems are of the research type at the present time. Japan has purchased some aligners from Karl Suess GMBH in Germany and work is being pursued on more advanced types of aligners at NTT, Matsushita, Canon, and Sumitomo Heavy Industries.

Beamlines

The function of the beamline is to transfer X rays from the storage ring to the aligner. The beamline is a long evacuated pipe or chamber several meters long with its own control and vacuum system (Ref. 3.1, Fig. 3.1). It is isolated from the synchrotron by front-end valves, one of which is usually a fast acting "shutter" that will close rapidly to protect the storage ring vacuum when a leak is detected. Valve closing times of 100-200 ms are typical.

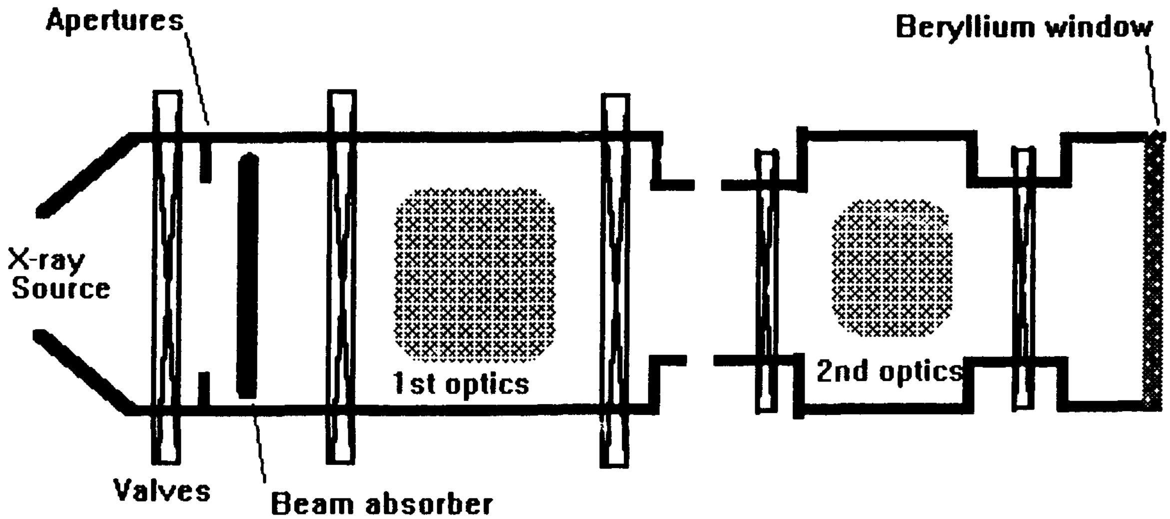


Figure 3.1. Typical Lithography Beamline Configuration

The beamline also contains one or more chambers containing the X-ray optics. The optics installed in these chambers is used to expand the beam and translate it into a useable form for the aligner. The optics consists of single or multiple mirrors which translate the beam to scan one axis of the exposure field. In some systems, a fixed mirror is utilized in the first mirror box to filter out the high-energy spectrum from the storage ring, to expand the beam in one axis, and to provide a few degrees of tilt to the beamline (deflecting the beam downwards from the horizontal position for safety reasons). The latter is important since the radiation generated from electrons hitting the walls of the ring is not in the direct line of sight of a tilted beamline. A translating mirror is then used to expand the other axis of the field and to scan the beam over the mask field. Multiple mirrors are utilized to minimize scanning losses due to a non-linear beam shape. Two such parallel mirror systems have been reported by NTT (Ref. 3.1). Canon uses a fixed cylindrical mirror in the beamline to expand the beam to a 30 x 30 mm field on the mask. Gold is the most common coating material for the mirrors; however, NTT has reported some work using platinum (Pt) mirrors. The surface finish is very important, and the most advanced polishing and etching techniques are used in the fabrication of mirrors.

A membrane window is used to separate the vacuum in the beamline from the aligner. This window is usually a thin beryllium foil (less than 25 μm thick). Kapton foils have also been reported; however, they show some lifetime problems. In some beamlines, an acoustic delay line consisting of a series of baffles is placed before the beryllium window. Its purpose is to decrease the propagation time of incoming gas in case of window breakage, and to allow sufficient time for the fast action valve to close.

To assist the pump down and out gassing of the beamline, a bake-out system is installed that consists of strip heater tape wrapped around the beamline and its components. Additional insulation is wrapped around it to allow the ebullient to be baked out at relatively high temperatures. All of the beamline components, including several ion pumps and valves located along its length, are computer controlled and are interfaced to the storage ring operational and safety systems. In some installations a small computer is used for beamline control. It generally will be interfaced to a larger computer that controls the ring facility.

The beamlines used in Japan today are generally of the research type and have been constructed by their users. At the present time, there is no company selling beamlines as a product line for lithography. Beamlines are built on an individual basis and are tailored to their applications. There are five beamlines installed and operated by semiconductor companies at the KEK facility in Tsukuba for lithography applications, and these are of the research type. The beamlines at NTT Atsugi and SORTEC are considered to be developmental and will later be replicated for those facilities. The NTT facility will have nine beamlines installed by the end of 1991, with Fujitsu and Toshiba using beamlines installed at that facility. Table 3.1 shows the status and description of beamlines installed in the various Japanese facilities visited by the team.

Table 3.1
Beamline Status

Location	Type	Optics	Remarks
NTT KEK	Research	Experimental	
FUJITSU KEK	Research	Experimental	
HITACHI KEK	Research	Translating Mirror	Optics Research
NEC KEK	Research	Experimental	
NTT Atsugi	Development	Two Mirror	9 in 1991
SORTEC	Development	Scan Mirror	
MITSUBISHI	Development	?	?
IHI "LUNA"	Development	Scan Mirror	Oper 6/91
SUMITOMO HI	Development	Scan Mirror	Oper 1/90

ALIGNER ELEMENTS OF PROXIMITY X-RAY EXPOSURE SYSTEMS

Mask/Wafer Aligners or Steppers

The mask/wafer aligner for a storage ring X-ray lithography system is operated with the semiconductor wafer mounted in a vertical position on some form of a vacuum chuck held in close proximity to the precisely aligned patterned mask. The aligner contains mechanical devices to load the mask and wafer from a clean room environment or a SMIF box. Manual single-wafer loading/unloading, or cassette loading/unloading, may be utilized in research types of tools to handle the mask and wafers. The wafer size may range from 100-200 mm in diameter.

To move the wafer to the next exposure field and to position the wafer with respect to the mask, Japanese aligners use two main types of coarse drives for their vertical XY tables. Canon is presently using linear air bearings for its XY table guides, and cylinder-type actuators, which are comprised of ball lead screws and DC motors. NTT is using an air-bearing lead screw that it has developed for both the X and Y axes. Both companies use flexure plates for the fine positioning of the wafer. Piezo electric actuators are used to position the mask.

One of the most critical components of the X-ray aligner is the alignment system. Alignment systems for X-ray lithography aligners being used in Japan are of two types. Both types process the combined signals obtained from the alignment marks on the mask and the wafer. These marks are gratings or linear zone plates. NTT and Matsushita have combined the gratings with optical heterodyne interferometric techniques (Ref. 3.2) and Sumitomo Heavy Industries is using a dual chromatic focus technique utilizing the same lens at two wavelengths. A similar alignment system, utilizing a dual-focus lens at two orthogonal states of light polarization, was originally utilized in X-ray lithography systems at Bell Laboratories (Ref. 3.3).

For 0.25 μm ground rules, the alignment system must be able to align the mask to the wafer with a total three sigma error of less than 0.05 μm. None of the Japanese systems have yet achieved this level of performance. The best reported performance is by NTT using an optical heterodyne system (0.1 micron, 3 sigma).

Mask/Wafer Environments

In order to provide heat transfer from the mask/wafer during X-ray exposure, a heat-conducting environment is required. Several types of environments have been utilized: air or nitrogen at atmospheric pressure, helium at atmospheric pressure, and also helium at low pressure. Helium offers little attenuation to the wavelengths of interest, and has a short mean free path capable of effective heat transfer down to pressures of about 20 torr. Because of throughput considerations, an environment of helium at atmospheric pressure is preferred. The Japanese have shown and reported work in all of the above environments. Air at atmospheric pressure is used by NTT and helium at low pressure by Canon. Variations of these environments are used by others.

The mask format used in the aligners has not yet been standardized. At the present time the NTT format is a de-facto standard. Similar formats are presently used by Dai Nippon and Toppan for their masks. (Mask materials and formats are covered by Dr. H. Smith in Chapter 4.)

Table 3.2
Aligner Status

Company	Remarks	No. of tools
Canon	Fixed optics-develop	Two prototypes
Matsushita	SORTEC develop tool	Development tool
NTT Atsugi	Development tools	1 Suess, 2 Dev Prototypes
Sumitomo Heavy Ind.	Development tool	1 prototype

FUTURE TECHNOLOGIES

There is also some work going on in Japan on projection optics. While it was not discussed on this trip, the literature indicates that Canon, Nikon, and NTT are doing research on projection X-ray optical systems. These systems will be completely different than the proximity X-ray systems in development today, as they are targeted to be reduction systems similar to today's optical reduction systems. They will use longer exposure wavelengths than the proximity X-ray systems and will require completely different technologies for the mask, X-ray optics, optical coatings, resists, and possibly the source, than proximity X-ray exposure systems.

SUMMARY

Japanese researchers and manufacturers are developing all of the key elements necessary to put together an X-ray production exposure system. While no one manufacturer has made the commitment to manufacture production exposure systems, many organizations have made major commitments in resources to develop the necessary elements. Other companies (Toshiba, Sumitomo, Matsushita, Fujitsu, etc.) have the experience and expertise necessary to integrate the exposure system when it is required.

There are two projects in the US which are addressing development aligners. There is a DARPA contract with SVGL (formerly Perkin Elmer) to produce a development exposure system which will be installed at the University of Wisconsin. This has suffered schedule delays because of the sale of the responsible Perkin Elmer division to SVGL. IBM has contracted for and is working with Karl Suess GMBH (a German company) on a development aligner for its facility in East Fishkill, New York. Neither of these projects has the alignment capabilities necessary to do 0.25 μm ground rules and will require improvements. The Japanese have more resources dedicated to the key elements which will be necessary for production exposure systems.

All of the major semiconductor manufacturers believe that optics will be extended with the use of phase shifting mask technology and have been reluctant to commit the resources necessary to integrate and produce a production exposure system for X ray. There is great uncertainty as to how far optics can be extended and, if the 256-megabit memory can be done optically, the immediate commitment to a production system will not occur. IBM and the major Japanese manufacturers have positioned themselves to have it available if necessary. Further development of the key elements will continue until necessity dictates that the X-ray solution be used.

The Japanese are doing research on projection X-ray reduction systems. Practical systems will probably not be available until after the turn of the century because of the amount of research and development work required. Bell Laboratories has demonstrated feasibility for this type of system and is believed to lead the world in this technology.

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CHAPTER 4

X-RAY MASK TECHNOLOGY

Henry I. Smith

INTRODUCTION

X-ray mask technology in Japan is well developed and differs in many significant ways from the technology being pursued in the United States by IBM, ATT, and Hampshire Instruments. In addition to extensive research and development activities in large microelectronics corporations, there are three commercial suppliers of X-ray masks in Japan: Dai Nippon Printing, Toppan Printing, and Hoya. Nippon Telephone and Telegraph (NTT) played a key role in the late 1970s in setting a direction for mask development in Japan. Among the most knowledgeable people in Japan today, there appears to be a consensus that the materials aspects of X-ray masks are solvable by straightforward engineering. There is significantly less confidence that the overlay and critical dimension (CD) control problems of e-beam patterning will be so easily solved as minimum feature sizes head toward 0.1 μm.

MEMBRANE MATERIALS

Figure 4.1 is a schematic of the most widely used mask format. In the United States both IBM and Hampshire Instruments utilize B-doped, single-crystal silicon (Si) membranes. No one in Japan pursues this approach. In Japan, deposited materials such as Si-rich silicon nitride (Si_3N_4 (i.e., SiN)) and silicon carbide (SiC) are preferred as membrane materials.

In the late 1970s, NTT developed a process for depositing stress-controlled Si-rich SiN. Membranes of this material, only 1.0 μm thick, are extremely strong, optically transparent, and readily produced by conventional integrated circuit (IC) equipment. NTT also developed a tantalum (Ta) absorber technology. The NTT technology was licensed to several laboratories in Japan; as a result, the combination of SiN and Ta is still the dominant approach (Ref. 4.1). However, several groups have deviated from this path and have developed high-quality SiC membranes (Ref. 4.2) and tungsten (W) absorber technology (Ref. 4.3).

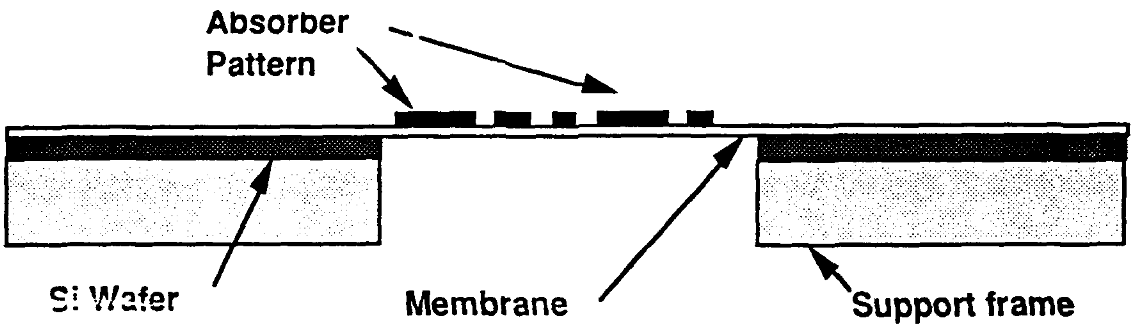

Figure 4.1. Schematic of the Most Widely Used X-ray Mask Architecture. A Si wafer is bonded to a rigid frame (typically Pyrex or other expansion-matched glass). The membrane is formed by etching the Si from the back side.

SiC is preferred over SiN because of a higher Young's modulus (4.6×10^{12} dynes/cm^2 versus 1.6×10^{12} dynes/cm^2 for Si_3N_4) and freedom from radiation-induced stress change (Ref. 4.4). Recent measurements at Hitachi, however, have shown that radiation damage is absent in SiN if the oxygen content is kept below 1% (Ref. 4.5). Currently, SiC is not as homogeneous as SiN, nor is it produced in standard IC equipment. Perhaps several additional man-years of development are required before SiC can be made to achieve the quality and stress control achievable today in SiN. It appears that the United States lags Japan (and Europe) in both SiN and SiC membrane technology.

ABSORBER MATERIALS

In the United States, at IBM and Hampshire Instruments,the standard absorber material is electroplated gold. No one in Japan is pursuing gold. Instead, Ta and W are the preferred materials, because they can be etched in a gaseous plasma. It is believed that such dry processing produces fewer defects than electroplating. Moreover, Ta and W are refractory and hence stable. Gold, on the other hand, undergoes grain growth and stress change even at the modest temperatures involved in resist stripping, etc. Stress control in Ta and W requires precise control of deposition parameters, which in Japan is achieved by open-loop processes. With regard to stress control, the technology in some U.S. research labs appears to be slightly ahead of developments in Japan (Ref. 4.6).

ABSORBER PROCESSING

Both Ta and W can be etched in fluorocarbon plasmas. Several gas combinations, operating pressures, and types of apparatus are used in Japan. In general, the thickness of Ta or W used is about 0.8 μm, sufficient to provide contrast far in excess of 10 to 1 (e.g., 20 or 30 to 1). Many Japanese researchers the JTEC panel talked to were concerned that as line widths approach 0.25 μm and finer, CD control in high-aspect-ratio absorbers will be a problem. For this reason the excess contrast will probably be trimmed. Also, W may supplant Ta because of its higher absorptivity.

The X-ray mask process licensed by NTT called for patterning of the absorber prior to etching away the Si substrate to create the membrane. Reasons given for this strategy were (1) difficulty of cooling membranes during absorber etching, and (2) the fear of consequences should a membrane shatter accidentally in an e-beam writing system. Some groups that have studied the NTT approach believe it can lead to pattern distortion, and thus patterning after membrane formation is preferred (Refs. 4.2 & 4.7).

MASK FORMAT AND GAP CONTROL

In Japan, some groups use a circular membrane, others a square format, indicating that a standardized format has not been established. The square format has the advantage that the Si substrate can act as a "frame" for the pattern being exposed. It was unclear from panel interviews in Japan if distortion was greater in one format than the other.

The Si wafers upon which X-ray membranes are created are always bonded to a thick, stable support ring. Some groups use Pyrex for the ring, others use SiC, and one (Hoya) uses a new glass, SD-1, which matches the thermal expansion of Si more closely. Both epoxy and anodic bonding are used to attach wafers to support rings. Alignment marks are always located on the membrane, never outboard in windows as in the IBM technique.

Limited data was available on mask flatness (Ref. 4.2). None of the Japanese groups use a mesa-rim technique (Fig. 4.2). In this regard, technology in some U.S. research labs is ahead of what was seen in Japan. Membrane flatness is intimately connected with mask-to-wafer gap control. This fact is appreciated in Japan; hence, improvements in flatness can be expected in the future. With the adaptive pin chucks that have been developed in Japan (Ref. 4.8), combined with mesa-rim techniques, gaps below 10 μm should be achieved. Several Japanese groups estimated that minimum gaps of 10 μm were feasible in production. This corresponds to minimum features of 0.1 μm.

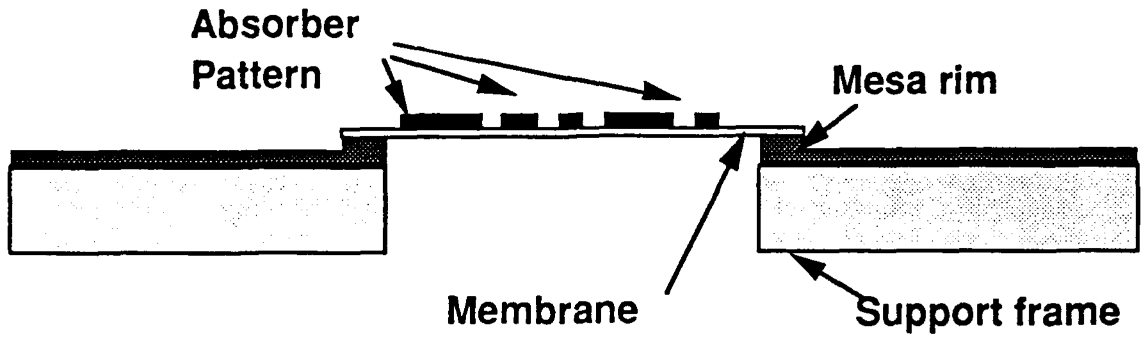

Figure 4.2. Mesa-Rim X-ray Mask Architecture. Only the portion of the X-ray mask substrate that contains the absorber pattern, plus the narrow rim, come in close proximity to the substrate. This facilitates small gaps (< 10 μm) between mask and substrate.

E-BEAM LITHOGRAPHY

E-beam techniques for patterning 0.5 μm features are available at most laboratories; however, many researchers in Japan expressed concerns about CD control and overlay for features below 0.5 μm. Most believed that patterning could be done on top of W- or Ta-coated membranes (Refs. 4.2 & 4.3); that is, that proximity-effect correction algorithms combined with high operating voltage (50-75 KeV) could circumvent backscattering problems.

INSPECTION AND REPAIR

The JTEC panel noted a surprising lack of effort in mask inspection and repair in Japan. No satisfactory explanation was given for this. At least two of the panel's hosts commented that they expect the inspection and repair tools to be developed in the United States, and that their companies will purchase this technology from U.S. vendors when the tools are needed.

SUMMARY

High-quality research in X-ray mask technology is going on at many separate locations in Japan. Full reports of much of this research have appeared in the technical literature (Refs. 4.1-4.8). There seemed to be a consensus that materials for X-ray masks are adequate now, although improvements will continue to be made. The major areas of concern were overlay in e-beam patterning, and CD control in pattern transfer. Many of the researchers interviewed expressed the view that whenever X-ray masks are needed in quantity and high quality, the current shortcomings can be overcome quickly.

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CHAPTER 5

RESISTS FOR X-RAY LITHOGRAPHY

R. Fabian Pease

INTRODUCTION

The relief image in a resist film on top of the thin film of circuit material is the final result of the lithographic process (Fig. 5.1). The term **pattern transfer** is used to describe the subsequent process of transferring the resist image into the circuit material (such as by etching).

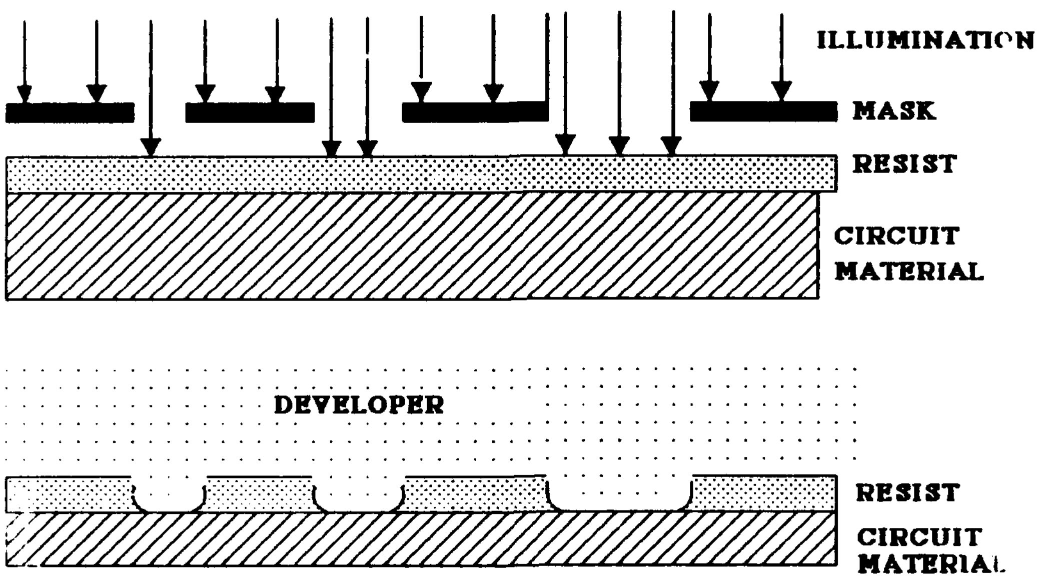

Figure 5.1. The Basic Microlithographic Process for Positive Tone Resist

The desirable technical properties of the resist film are adequate sensitivity to the patterning radiation; adequate resistance to the pattern transfer process (including adhesion to the substrate during this process); high contrast to discriminate between the nominally unexposed and exposed regions of a low-contrast aerial image; high resolution; and low defect density. Definitions of the relevant resist film properties are as follows:

Sensitivity. Sensitivity is usually expressed as the minimum incident dose needed to give the required relief image on developing; the units are mJ/cm^2 for X-ray lithography (XRL) and optical lithography (OL), and $\mu C/cm^2$ for electron- beam (or e-beam) lithography (EBL).

Contrast. Contrast is expressed as the slope of the steepest part of the curve of (developed resist thickness/initial thickness) versus $\log_{10}$(dose).

Resolution. Resolution refers to the minimum line width that can be resolved in a pattern of equal lines and spaces. Since this depends critically on the resist thickness (as well as the details of the processing), the term can only be used qualitatively: **high** means that features of 100 nm and below can be resolved in films 0.25 μm thick, e.g., poly (methyl methacrylate) (PMMA); **medium** can yield 0.25 μm features in 0.35 μm thick films (e.g., most positive photoresists).

Defect density. Defect density is rarely quoted because it appears to depend far more on the process conditions and thickness than on intrinsic material properties.

Tone. The tone of the resist can be **negative**, for which the unexposed regions are dissolved away on developing, or **positive** for the reverse behavior.

All resists described in this chapter are polymeric and are applied by spinning. Both X-ray resists and e-beam resists are considered, since the latter are necessary for making the XRL masks. Optical (UV and deep UV) resists are not explicitly described; their action is a good deal more complicated because they bleach on exposure and they need specific sensitizers. However, the immense effort that has gone into UV photoresists has helped in developing both X-ray and e-beam resists. For good general references, see Thompson (Ref. 5.1) and King (Ref. 5.2).

Evolution of Resist Technologies

Early resists for both XRL and EBL had large molecular weights and chemical groups that gave large responses to small incident doses (e.g., the epoxy groups). Although very high sensitivities were obtained, the rheological effects, particularly swelling during development, gave very poor profiles: aspect ratios higher than 1:3 were difficult to obtain, and the contrast was about unity. Work on negative cross-linking resists concentrated on ameliorating these undesirable effects. Some resists emerged that proved reasonably practical for features down to about 2 μm; however, it was clear that for submicron work a radical improvement was needed.

One approach was the multilayer resist (Ref. 5.3) in which a submicron pattern is delineated in a very thin sensitive top layer, and this layer is subsequently transferred into the much thicker lower layer by a nonselective, high-resolution process such as reactive ion beam etching (Fig. 5.2). An attractive embellishment of this process is the silylation process (Ref. 5.4) in which the top surface layer is generated by the exposure process and subsequent chemical treatment instead of requiring a separate application (Fig. 5.3).

A second approach was the development of positive resists in which the exposed regions dissolve away preferentially. This increased dissolution comes about through reduced molecular weight as a result of chain scission, through local stress induced by the local evolution of gas, or by more subtle processes. The developing action is one of etching at a surface rather than the bulk leeching action of the negative cross-linking resists. As a result, there is less swelling so sharper profiles are possible. Furthermore, contrast depends on the selectivity of the dissolution process, and values higher than 3 have been claimed (a value of 3 suggests that a twofold difference in doses in nominally exposed, and unexposed, regions will give an adequate relief image).

Positive resists tend to require larger doses than do their negative cross-linking counterparts, and this has led to the push for higher flux sources: field emission or shaped beam in the case of electrons and synchrotron radiation, or laser plasmas in the case of X rays. The complementary push has been to enhance the sensitivity of positive resists. The original positive resist for X rays and e-beams is poly (methyl-methacrylate) (PMMA), which exhibits both high resolution (feature sizes below 20 nm) and high required dose (about 100 $\mu C/cm^2$ for 10 KeV electrons or 500 J/cc). Poly (butene sulfone) (PBS), introduced in 1975, requires only 1 $\mu C/cm^2$, but it has proved to be deficient in terms of etch resistance; however it still remains a popular positive resist for electron beam mask making.

Two-component resists were also investigated: The first type are positive photoresists in which a photoactive compound (PAC) is dissociated on exposure to render the local regions of novolak resin soluble in the aqueous alkaline developer. The required dose is one-third of that needed for PMMA, and the resistance to reactive ion etching (RIE) is significantly improved. The second type, only just being introduced, is referred to as **chemically amplified** resists (Ref. 5.5). These materials are also two-component, in which the PAC, on exposure, yields

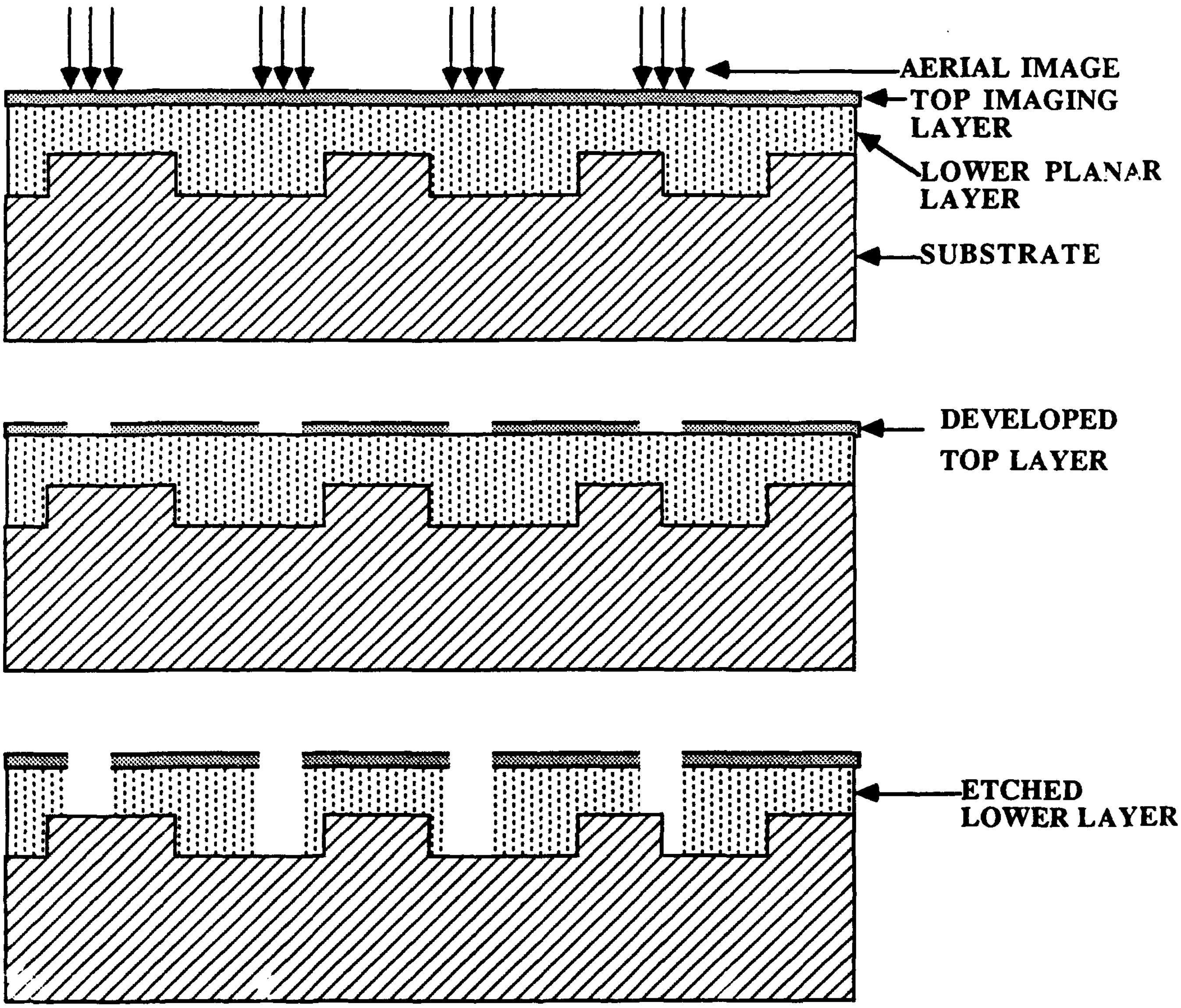

Figure 5.2. Schematic of Multilevel Resist Process

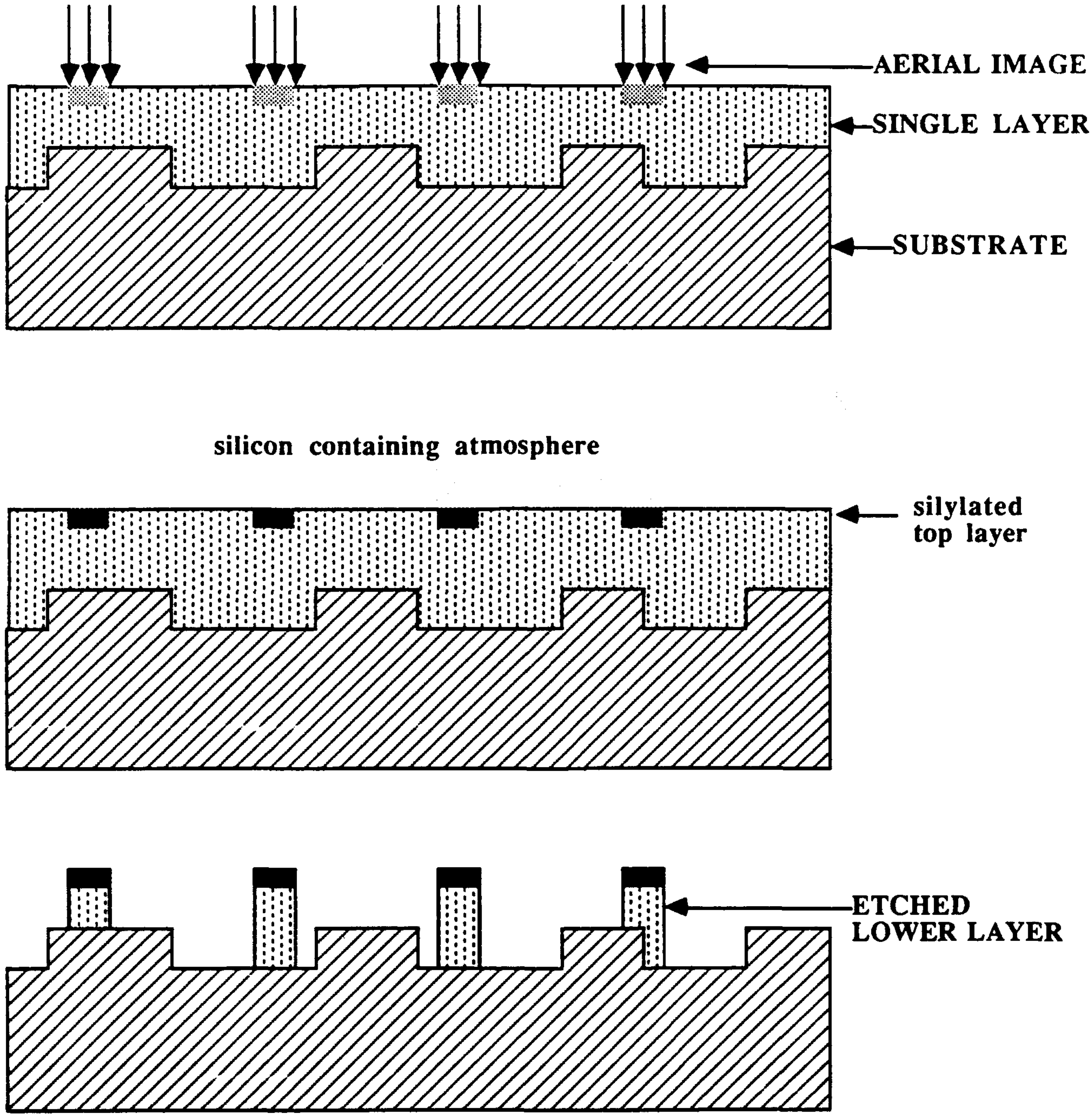

Figure 5.3. Schematic of Silylation Resist Process

reaction products that bring about cross-linking or chain scission of the host polymer, and hence render the exposed or unexposed regions insoluble to the subsequent developing. Thus, chemically amplified materials are negative or positive acting, but because of the amplification step, they do not require the large molecular weights to give the required sensitivity. They therefore avoid the swelling problems mentioned earlier; feature sizes as small as 0.15 μm have been observed for a dose of 3 $\mu C/cm^2$ (i.e., they are about 30 times as sensitive as PMMA).

X-RAY AND E-BEAM RESISTS IN JAPAN

This chapter describes resists both for XRL per se and for the EBL used for making the mask. There has been an active resist industry in Japan for at least twenty years. Japanese semiconductor manufacturers use resists produced both in Japan and abroad. Indeed, Hitachi, which has one of the best-established resist programs, is using German- and U.S.-made resists as well as its own. An excellent summary of the state of the Japanese resist industry in 1988 is "Japan R&D Trend Analysis on Advanced Materials. Report No. 1:Photoresists," prepared by KRI International; this report will be referred to as "KRI" (Ref. 5.6).

Most resist research in Japan, as elsewhere, is directed towards optical lithography, because that is by far the largest market: ¥16 billion for optical ultraviolet (UV) resists for IC fabrication, ¥2.1 billion for e-beam resists, and ¥0.1 billion for deep UV resists (KRI). Market figures for X-ray resists do not even appear on KRI's list.

The major companies with active X-ray resist programs are Tokyo Ohka Kogyo (TOK), Japan's largest supplier of photoresists with 60 percent of the market; Japan Synthetic Rubber (JSR) with 20 percent of the market; and Hitachi Chemical, Chisso, Daikin, Fuji Chemical, Somar, Toray (Tokyo Rayon), and Toso (Tokyo Soda). All were reported in KRI to be manufacturing e-beam or X-ray resists; however, JSR informed JTEC panelists that it no longer manufactures e-beam or X-ray resists because of low demand.

Many other organizations in universities, government laboratories, and industry have research or development programs in e-beam and X-ray resists. The following sites visited by the JTEC team are reported in KRI to have ongoing R&D programs in e-beam and X-ray resists: JSR, Hitachi Central Research Laboratory, Dai Nippon, NTT, Matsushita, Oki, NEC, Toshiba, Fujitsu, and ETL. However, during panel visits only JSR, Hitachi, Matsushita, Toshiba, and Fujitsu reported active programs in resist materials. Of these, only Toshiba, Hitachi, and Fujitsu were actively developing e-beam or X-ray resists. Work at the other sites appears now to be restricted to developing recipes for processing resists obtained externally, although it should be pointed out that NTT's e-beam resist development has been carried out at the Ibaraki location (Ibaraki Electrical Communication Lab.), not at the Atsugi location the panel visited.

Table 5.1, drawn from JTEC site visits and the published literature, describes the status of X-ray and e-beam resists available from Japanese sources. An equivalent summary table of R&D in e-beam and X-ray resists would be far too bulky to be useful; instead, some of the more significant areas that are being pursued are described below.

Conducting E-beam Resists

Charging of the irradiated workpiece can cause defocusing and displacement of the incident beam, so having a conducting resist is clearly an attractive move; however, only a small conductivity is required to leak charge away at a sufficient rate.

One approach, pursued by Tamamura and his colleagues at NTT Ibaraki, is to use amorphous carbon films as the lower layer of a bilayer resist structure (Ref. 5.7). The carbon films have twice the resistance to the RIE process used for etching silicon (e.g., using $CBrF_3$), yet can be patterned with an O_2-based RIE process. The film can be prepared by a variety of techniques including plasma CVD or ion beam deposition and are typically 250 nm thick. Using a top layer of silicon-based resist SNR (described in the next section), the NTT scientists have obtained, in silicon, etched line/space patterns of 200 nm period and 600 nm deep. They do not report any experiments either on measuring surface charging or on pattern placement accuracy in a high-precision pattern generator; however, in experiments subsequent to their letter (Ref. 5.7), they report that the conductivity of the carbon can range from 10^{-8} to 10 S/cm, depending on the substrate temperature (Ref. 5.8).

A second approach is to employ ammonium poly (p-styrene sulfonate) (AmPSS) as the conductive layer in place of the carbon film (Ref. 5.9). The sheet resistance of a 2 μm thick film was 10^6/square. Although surface charging was not directly measured, Todokoro et al. demonstrated the complete absence of detectable distortion of a test pattern, whereas a control sample exhibited distortion ranging from 100-300 nm. Even writing on an unmetallized quartz substrate appeared to be distortion-free. They also quoted a five-fold improvement in alignment accuracy.

As far as the JTEC panel is aware, there is no significant effort in the United States to develop conducting e-beam resists.

Table 8.1
Japanese X-ray and E-beam Resists

Source	Material	Req'd Dose*/Tone	Comments
TOK	OEBR-100	100 $\mu C/cm^2$/+ or 500 mJ/cm^2	PMMA; single component +ve
	OEBR-1010	N/A**/+	poly (methyl isoprenyl ketone)
	OEBR-1030	N/A**/+	poly (MMA-acrylonitrile)
TOSO	CMS	200 mJ/cm^2/-	chlorinated poly(methyl styrene) cross-linking; required dose depends on MW and %Cl***
	NSR	N/A**/-	Appears to be a silicon containing negative resist (SNR) requiring 3 μC/cm2
	CER	N/A**/-	AmPSS conducting layer developed with Matsushita Used with SNR top layer
Daikin	FBM	N/A**/+	poly(hexafluorobutyl-methacrylate)
Hitachi	RE-5000P	5 $\mu C/cm^2$/+	Novolak/poly(methylpentenesulfone) Good etch resistance Also used as X-ray resist
Toray	EBR-9	3 $\mu C/cm^2$/+	poly(trifluoroethyl-a-chloroacrylate) Popular resist for mask making
Chisso	COP	0.4 $\mu C/cm^2$/-	The original e-beam resist for masks
	PBS	1 $\mu C/cm^2$/+	Sensitive +ve resist for masks Both PBS, COP originated at Bell Labs
Fuji Chemical	FMR-E100	N/A**/+	poly(acryl amide-cyanoacrylate)
JSR	MES-X	80 mJ/cm^2/-	chlorinated polystyrene (PdLa)
Mitsubishi	XPB	250 mJ/cm^2/+	Used for contact hole lith in 1-Mbit DRAM

* $\mu C/cm^2$ for 20 kV electron exposure - mJ/cm^2 for X rays exposure.

** N/A. Required dose and exposure conditions not available at the time of writing.

*** KRI, p. 84.

Silicon-Containing Resists

Since the original work on the improved ion etch resistance of polymeric resists through the incorporation of silicon, there has been continual effort around the world to bring such materials into commercial use. The simplest approach is to incorporate the silicon nonselectively as part of the original deposited film. A more elegant approach is to incorporate the silicon selectively into the exposed surface layer regions by heating the exposed workpiece in an atmosphere containing a silicon-containing compound such as hexamethyldisilazane (HMDS) (Fig. 5.3). This process is appealing because only the top layer, less than 100 nm thick, need be exposed; thus, the radiation need not penetrate further and the proximity effect in e-beam lithography is reduced, yet there is no need to lay down a separate defect-free film only 100 nm thick.

Again, the Tamamura group at NTT Ibaraki has been prominent in the published work from Japan (see, for example, Ref. 5.10). The main chain of the silicon-containing negative resist (SNR) is poly(diphenylsiloxane) (PDS) with chloromethyl groups for cross-linking. This material is used as the top layer of a two-layer structure, with AZ 1350 photoresist as the lower. The required dose to obtain Tn=0.5 was 5 $\mu C/cm^2$ doe 20 KeV electrons and Mw = 40,000; the contrast was about 2. High-aspect-ratio line/space patterns of 0.2 μm half-pitch were obtained.

The selective silicon approach is being vigorously pursued by JSR in cooperation with UCB in Belgium, one place where the process originated and where the acronym DESIRE (Diffusion Enhanced Silylating Resist) was coined (Ref. 5.4). The main application is for UV and deep UV exposure, but the process is also applicable for high-precision e-beam lithography. The material is quite similar to conventional, two-component positive photoresist. Following exposure, silylation takes place selectively at the reactive hydroxyl groups of the novolak resin. Following silylation, the relief image is formed by dry etching. One of the main problems has been the formation of a residue ("grass") following the etching. JSR claims to minimize this by being particularly careful to minimize contamination with heavy metal ions.

Chemical Amplification

All the main resist organizations are developing versions of chemically amplified resists based on light-induced acid-catalyzed hydrolysis (see, for example, Ref. 5.11). Because of their sensitivity, these resists are obviously attractive for DUV lithography, and the amplification mechanism can be adapted to give either positive or negative action; the principle can also be used for e-beam and X-ray resists. For example, JSR is developing a positive tone material designated PFR KRF-B7 for use at 248 nm wavelength. A required dose is $20 mJ/cm^2$ and will be used for 0.3 μm features when exposed with projection optics of NA=0.42.

During the JTEC visit, the JSR team reported some anomalous surface effects on developing, and it conceded that "There is much we don't understand about this resist system."

SUMMARY

There is a large, diverse developmental effort in resist technology in Japan. The exploratory work seems to be well reported in English, both at conferences and in technical journals. Several large companies are investing heavily in this area. The main effort is in photoresists for deep UV, with secondary efforts for e-beam and X-ray resists. Resists are not perceived as a bottleneck for XRL; this may follow from the general belief that synchrotron radiation is the only practical source for XRL manufacturing. One development unmatched elsewhere is the work on conducting resists for e-beam lithography. This is aimed both at mask making and at direct write; the cell projection approach Hitachi is developing may be very susceptible to charging because of the high currents envisaged. In general, the state of resist technology in Japan is equivalent to that elsewhere, although the resources being applied appear greater than that in the United States alone.

Projections for the Future

Since synchrotrons are considered to be the only practical source of X rays for manufacturing very large integrated circuits (VLSICs), there is relatively little emphasis on developing resists specifically for XRL. For example, during the trip to Japan, JTEC panelists came across no work on enhancing the sensitivity by tailoring the chemical content to be near an absorption edge (Ref. 5.12). The general attitude panelists encountered is that e-beam resists will be adequate. The panel knows of no fundamental factor such as shot noise that sets, say, 30 mJ/cm^2 as the lower limit of required dose. The considerable activity in e-beam technology, including resists, should lead to significant advances in the precision of the patterns generated (see, for example, Ref. 5.13).

Table 5.2
Key Research Personnel and Facilities for Resist R&D

T. Nakayama	TOK, 1590 Tabata, Samukawa-cho, Kohza-gun, Kanagawa-ken 253-01 Japan
M. Sasago	Matsushita Electric
N. Nomura	Matsushita Electric
K. Ueno	Hitachi CRL
S. Nonogaki	Hitachi CRL
M. Kataoka	Toray Industries, 1-1, Sonoyama 1-chome, Otsu-shi, Shiga 520, Japan
N. Yoshioka	Mitsubishi Electric
M. Hikita	Polymer Section, NTT ECL, Tokai, Ibaraki 319-11
T. Tamamura	Polymer Section, NTT ECL, Tokai, Ibaraki 319-11
Y. Matsumura	Research Director, Electronics Research Laboratory
T. Takahashi	Chief Scientist, Electronics Research Laboratory, JSR
Y. Harita	Manager, Electronic Materials Department, JSR
Y. Yumoto	Chief Chemist, Development Center, JSR

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CHAPTER 6

X-RAY LITHOGRAPHY SYSTEMS INTEGRATION AND MANUFACTURING INSERTION

Gene E. Fuller

INTRODUCTION

As outlined in the preceding chapters, it now appears that there are few, if any, remaining fundamental technical barriers to the individual component elements of X-ray lithography (XRL). Excellent progress has been made in the areas of sources, masks, and aligners. Suitable resists are available. Numerous development programs are currently in place to further refine these technology elements into robust manufacturing components.

The key unknown issues for XRL have moved to the topics of system integration, manufacturing insertion, cost-effectiveness, and future progress in alternative lithography technologies.

Surprisingly, the JTEC panel found in Japan relatively modest emphasis on these systems issues at the present time. As discussed below, the typical timeline for XRL shows introduction into full manufacturing in 1998. Many of the systems issues will be more fully addressed in the next three to four years.

XRL SYSTEM INTEGRATION

A complete XRL capability will include at least the following items:

- X-Ray Source
- Beamlines
- Steppers
- Resist
- Masks
- Operating Control System
- Resist Process
- Process Control
- Factory Automation
- Facilities
- Safety
- Device Architecture

Systems integration involves the definition, selection, and implementation of these elements to create a quality production capability for the semiconductor manufacturer. Integration tasks range from developing the technical approach through establishing operating procedures.

An important factor in any complex technology is coordination of interfaces and operating standards for the major subsystems. For example, in the case of XRL, the mask technology must be compatible with the X-ray photon energy used, and the resist technology must be compatible with the available intensity of the delivered X rays. These subjects have been the topics of numerous publications, workshops, and debates since the inception of XRL two decades ago. There are many sets of coordinated approaches to these fundamental compatibility issues, and the panel found no major differences in the strategies being pursued in Japan from those being pursued in the rest of the world.

Even though there are many plausible approaches to XRL technology, it is likely that R&D funding limitations will lead to only one or two source/mask/aligner combinations being fully developed to production worthiness. The selection of final combinations will likely be determined by the marketplace. There was little evidence of technology selection or standardization either by agencies of the Japanese government or by any consortium or trade association.

The next level of coordination and standardization, beyond the technology choices, involves mechanical and electrical interfaces. It is imperative that the mask and aligner be mechanically compatible in a single XRL system, but it also could be important to the user that masks be compatible with more than one brand of aligner.

A parallel situation exists in the widely practiced optical stepper technology. Optical steppers use masks or reticles that can be readily manufactured by any qualified supplier in the world, and in many cases, the masks can be used on several brands of optical steppers.

An attempt has been made in the United States, starting as long ago as 1982, to create mechanical standards for XRL mask outlines, mounting approaches, and alignment fiducials. This effort is unfinished, largely because the technology has continued to develop. It appears there has been no more progress in Japan than in the United States toward standardization. However, the panel heard in several locations that Semiconductor Equipment and Materials International (SEMI) Japan is currently discussing the formation of a working group in 1991 to draft standards for XRL.

A broader question beyond technology compatibility and interface coordination concerns the overall system integration and operation: Who is responsible for creating a manufacturing-quality lithography capability for the chip maker?

Traditionally, the semiconductor manufacturer has taken full responsibility for the construction of wafer fabrication facilities, equipment selection, and facility operation. Some interfacing of equipment, such as connection of a coater/developer track connected to an optical stepper, can be performed by a supplier, but in most cases, the semiconductor manufacturer (user) performs the integration function. It is also typical in the industry that wafer fabrication equipment is shipped from the supplier in a complete and ready-to-run state.

It has been suggested that an important, or at least desirable, feature in production XRL be the availability of "turnkey" lithography capability provided by a supplier. This would then require the existence of a systems integrator, who may or may not actually manufacture any of the hardware elements, to provide a ready-to-run lithography tool for the user. The integrator would select, install, and start up the X-ray source (presumably an SOR source), the beamlines, and the aligners. The integrator would also establish the overall lithographic capability. This generic approach has been widely and successfully used in many commercial endeavors, such as desktop computing, but is essentially untested in the semiconductor manufacturing world.

The panel found little evidence in Japan of any effort to create an overall system integrator approach for XRL. The panel was told that integration of the hardware (source, aligner, beamline) will be supported by the SOR suppliers, as desired by their customers, but it was not evident that "turnkey" lithography capability suppliers would evolve. Each of the semiconductor manufacturing companies visited stated that it expected to serve the (traditional) role of system integrator itself. This approach, of course, is also the approach taken by IBM at the new Advanced Lithography Facility in East Fishkill, New York.

There are several potential outcomes from the "self-integrator" approach:

> Industry standardization will become less important and more difficult to achieve than if a small number of systems suppliers served the industry.
>
> Only large players will be able to get an early start in XRL. The system integration task will require substantial effort to select the best system components and make them work together effectively. Smaller companies will be unlikely to make the investment required.

> Learning in the XRL industry will tend to be slower. Information gained within one company will not be shared with other companies to the same extent as it would if there was an independent system integrator.

System integration at both the component standardization level and the complete system operation level has not yet become a first-priority issue with either the suppliers or the users. Component standardization will likely be developed in the coming years. Standardization of complete systems through independent systems integrators may never occur.

DEVICE FABRICATION ISSUES

There are two major considerations regarding the application of XRL to actual production devices. First is the choice of the most appropriate circuit type or types for cost-effective application of XRL, and second is the technology impact of XRL on the architecture or process flow for the chosen device.

It is apparent that companies will not be able to "dabble" in XRL. The X-ray source of choice is currently synchrotron-based, which is large, expensive, and capable of supporting high production capacity. The expected complexity and cost of manufacturing quality XRL masks will dictate that the targeted types of integrated circuits to be produced by XRL will need to be high-volume devices.

The panel found virtually unanimous agreement that the first major production application for XRL will most likely be in the manufacture of dynamic random access memory chips (DRAMs). DRAMs are both high-volume products and the traditional process technology leaders. This agreement was expected, but there was no clear direction stated for ultimately expanding XRL to other high-volume applications such as gate arrays or microprocessors.

The impact of XRL on the target device architecture and/or process has been the subject of discussion for many years. The most obvious concern is the impact of the X-ray radiation on the device performance. In particular, it is well known that the performance of silicon dioxide films, which are ubiquitous in CMOS devices, is seriously degraded by even moderate levels of radiation. The performance degradation, which is largely a result of trapped charges near the oxide interfaces, can be reversed by straightforward annealing of the completed wafers, but the long-term reliability impact of repeated radiation and recovery cycles has not been examined in any detail. Subsequent radiation hardness and hot carrier degradation are two important concerns.

The panel questioned the semiconductor manufacturers visited on the topic of XRL-induced radiation damage, but it appears that very little work has yet been done to look at the long-term effects. Most of the radiation damage studies related to XRL have been directed toward mask damage. Of course, the mask sees many more exposures than any individual wafer, so the impact is more obvious. The use of silicon carbide for mask substrates greatly diminishes any radiation damage in the mask.

Other device fabrication issues that may arise with the use of XRL involve operational considerations rather than device damage or performance issues. A key attribute of XRL is its extremely stable linewidth control capability. It is typical that exposure variations as small as 5-8 percent in optical lithography can cause pattern linewidth variations of 10 percent or more. The analogous situation in XRL is variations as large as 50 percent in exposure cause pattern linewidth changes of less than 10 percent. While this stability is very beneficial to process control and repeatability, it removes the ability of the manufacturing process engineer to make small adjustments to the semiconductor device performance through size changes in the lithography patterns.

The expected difficulty in creating a 1X mask pattern with 0.25 μm features exacerbates the need for such adjustment. Conventional manufacturing requires feature size control of 10 percent, or 0.025 μm in this case. It is possible that this high degree of control will require a different approach to the lithography process or even a change in circuit device architecture.

A likely scenario for the introduction of XRL into production fabrication of integrated circuits is the application of XRL on only the most critical device layers, while the less critical layers are patterned through conventional optical means. This "mix and match" approach is generally the most cost-effective approach in the introductory phase of any new lithography technology. However, additional operational complications arise from the need to have multiple sets of mask-to-wafer alignment marks, multiple resist processes, and possibly different pattern distortion characteristics between proximity XRL and projection optical lithography. Each of these issues can be addressed and overcome, but it appears at this time that little effort is yet underway.

Finally, another stability feature provided by proximity XRL, namely freedom from optical distortion of the image, will need to be addressed. It is conventional to make small adjustments to the magnification and/or distortion characteristic of the image from an optical stepper to precisely match the preexisting pattern on the substrate wafer. The wafer patterns are typically not perfect, due to the impact of high-temperature processing and the stresses caused by various thin-film layers (oxides, metals). It will be necessary for an XRL process to be able to make small pattern adjustments, or else the wafer process will need to be further refined to minimize such wafer-induced distortions.

In summary, the device fabrication issues have only recently begun to be addressed by serious R&D efforts. Universally the target device type is a DRAM, but many other issues must be resolved before full production application of XRL can occur. Fortunately, it does not appear that any of these issues are of the fundamental "show stopper" category, but they will require time and effort to eliminate as concerns.

MANUFACTURING INSERTION ROADMAP

The important issues of technology development and systems integration are discussed above. The remaining major roadmap issue for XRL is the modularity of the XRL system. With the use of SOR-based sources, a fully configured, economically sound XRL system will have the capability of supporting 10 to 20 wafer alignment stations. This single unit of capacity is comparable to the entire lithography capability in many wafer fabrication facilities today. The threshold for entry into production XRL would seem to be at the level of a complete wafer production line. (Traditionally, most new technologies are introduced into manufacturing only on a small-scale replacement basis.)

The modularity issue surfaces in several ways. First, the initial XRL system is large and expensive. Instead of purchasing a small number of new optical steppers at a present cost of $2 million each, the user now faces the purchase of a system approaching $100 million for just the lithography capability and an equal or larger amount for dedicated facilities and other needed process equipment.

Perhaps even more importantly, the decision to use XRL is virtually irreversible. Unlike the purchase of a single new process tool, such as an optical stepper that can be removed if it proves to be unsatisfactory, the XRL-based wafer fab will be designed to work around the XRL system. If the XRL capability did not actually function properly, there would be considerable difficulty and expense in going to a fall-back strategy.

The operational reliability of the XRL system provides another challenge. Even if the reliability or "uptime" of the XRL system is "good," for example greater than 90 percent, the large size of the system and its central nature to the wafer fab operations will cause a shutdown of most fab operations if the lithography system, especially the SOR source, fails.

Two approaches have been discussed to deal with the modularity-related reliability concerns. The first is to install a duplicate system to serve as a backup in case of failure of the primary system. In addition to some potential operational difficulties in rerouting wafer flows, or possibly rerouting X rays, the overwhelming argument against this approach is economic. The semiconductor business is extremely cost-sensitive, and the cost to have a spare lithography system ready at all times as a backup simply cannot be tolerated. The panel did not find any of the Japanese semiconductor manufacturers visited supporting this approach. However, some of the individual component suppliers still believe it is a viable alternative.

Another approach that could be used to reduce the potentially catastrophic impact of a single system failure is to build enormous wafer fabs that can use up to 100 lithography alignment stations. Such fabs would have five to eight complete XRL systems. Clearly the initial investment is very large, but the resulting guarantee of production stability and achievement of customer commitments is very important to wafer fab strategy. This again leads to the conclusion that XRL introduction is most suited for high-volume DRAM wafer production lines.

An additional modularity issue is not related to production, but rather to the R&D phases of both process and product development. The availability of numerous facilities such as SORTEC in Japan and the storage rings at Brookhaven and Wisconsin in the United States is a vital part of the R&D capability for most semiconductor manufacturers interested in XRL development.

The availability of such research facilities reduces the barrier to semiconductor manufacturers engaging in research and initial development phases. However, for pilot lines or prototyping, it is generally required that the complete lithography capability be available in the fabrication facility. Thus, the modularity issue is very important.

In summary, the size and expense issues are manageable in the R&D and, potentially, in the full-production phases, but they may present significant barriers in the transition or pilot line phase.

TIMELINE

In all cases, timing discussions with the panel's Japanese hosts centered not around the availability of XRL technology, but rather around the product needs and the capability of existing lithography technology to meet those needs.

The most common answer to the panel's question, "When will XRL be used in volume production applications?" was 1998. The typical introductory device type is the 256 Mbit DRAM. The range of answers varied from 1995-96 for second-generation 64 Mbit DRAMs to 2000 for 1 Gbit DRAMs.

An alternative view of the introduction time for XRL centers on the ultimate linewidth capability of conventional and enhanced optical lithography. It is now widely predicted that optical lithography, including such enhancements as phase shift mask technology, will provide manufacturing capability down to and even beyond 0.3 m pattern linewidths. This covers the requirements for device types up to and including the complexity level of 64 Mbit DRAMS. Some optical equipment suppliers and semiconductor manufacturers believe that optical lithography can support manufacturing to and beyond 0.2 μm, which would cover the 256 Mbit DRAM class of devices.

It should be noted, however, that such advances in optical lithography are not considered easy or straightforward. In particular, the drive to sub-0.2 μm optical lithography will likely require the use of exposure wavelengths at or below 200 nm. This in turn may require new materials for reduction lenses or mirrors and other optical components, new resists, and improved light sources.

The single most important factor in the systems integration and manufacturing insertion of XRL into production wafer fabs is thus the future progress and resulting capability of the current lithography technology, namely reduction optical steppers. The worldwide market today for optical steppers is approaching $2 billion per year. The exact amounts spent by Japanese suppliers on R&D is unknown. However, a typical estimate of 10 percent of gross sales being fed back into R&D leads to the conclusion that at least $200 million per year is going into the advancement of optical lithography in Japan.

In addition to the stepper suppliers, both the Japanese mask suppliers and the semiconductor manufacturers themselves spend substantial amounts in lithography R&D. One of the highlights of the 1990 International Electron Devices Meeting was the appearance of several papers from Japanese semiconductor manufacturers describing the use of conventional optical lithography and phase shift mask technology to produce test patterns down to 0.2 μm linewidth. In addition, five Japanese companies reported prototype 64 Mbit DRAM chips at the 1991 International Solid State Circuits Conference. Both i-line (365 nm) and deep UV (248 nm) optical tools were used for the 0.3-0.4 μm patterning.

The JTEC panel was repeatedly told by the semiconductor manufacturers it visited in Japan that they had equal or larger programs in optical lithography development than in XRL development.

In summary, the timeline for XRL is not determined by the time needed for the full development of XRL but rather by the evolving capability of the ultraviolet technology. The most likely scenarios show production XRL arriving late in the 1990s or at the turn of the century.

SUMMARY

Systems integration and manufacturing insertion remain the largest open issues in XRL. It appears that these issues do not yet have top priority compared to many of the technical developments currently underway.

The four major categories of issues are complete lithography system capability, device fabrication, manufacturing insertion roadmap, and timeline. Each will require careful study in the future.

X-ray lithography integration is and will be driven by the large, vertically integrated system manufacturers, with strong support from the component hardware suppliers. The device issues, including both electrical and process factors, rest entirely on the semiconductor manufacturers, perhaps with support from research institutions. The roadmap and modularity barriers are addressed initially by research facilities and consortia, but the pilot line threshold problem likely belongs entirely to the end user. Finally, the timeline for the introduction of XRL into high-volume manufacturing use depends more on the evolution of alternate technologies, especially ultraviolet steppers, than on any limitations of the XRL technology. XRL can be ready in the 1998 time frame, if needed.

CHAPTER 7

ALTERNATIVE STRATEGIES

R. Fabian Pease

INTRODUCTION

In 1970 there were already vigorous efforts to find a successor to UV photolithography. Although light microscopes could resolve features below 1 μm, it seemed unlikely that it would be possible to manufacture components with features less than about ten wavelengths of the fashioning radiation. Therefore, the argument was made that some suboptical technique would be needed as minimum feature dimensions approached 1 μm. Today VLSI circuits with minimum features less than 2 wavelengths are in manufacture using the same radiation as in 1970 (UV in the wavelength range 365-436 nm). The exposure tools have evolved from contact printers to proximity printers to scanning projection aligners to two generations of reduction steppers. The resists have evolved from rubber-like, low-contrast materials to high-contrast materials that can yield high-aspect ratio features 0.25 μm wide when exposed with 248 nm deep UV light in developmental steppers (Ref. 7.1).

The choice of technology for semiconductor manufacturing is primarily governed by economics and technology; "show stoppers" are uncommon. With an unlimited budget, it would be possible to use ultraviolet lithography to manufacture ICs with features down to 100 nm, maybe even smaller. So to rely primarily on physical limits for guidance in choosing a technology is likely to be naive; such an approach led to the feeling that optical lithography would become prohibitively expensive at about 1 μm.

Estimating the cost of a technology is notoriously difficult. In the late 1970s, X-ray lithography was advocated as a low-cost alternative to new optical steppers that were expected to exceed the $200,000 cost of scanning projection aligners, with the argument that substituting an X-ray source for a UV lamp in a proximity printer was less expensive than installing projection optics. However, developing what are commonly referred to as the "support technologies," such as suitable masks and resists, proved to be uneconomical, especially as the requirements for alignment and feature size control became significantly tighter as minimum critical feature dimensions (MCD) decreased. As is pointed out elsewhere in this report, the solution to the X-ray resist problem in most places is to employ synchrotron radiation, but based upon this solution, the low-cost argument for XRL has lost a lot of force.

However, simply because relative costs were misjudged in 1979 doesn't mean that they shouldn't be examined now. Figure 7.1 shows how the capital cost of wafer exposure tools has increased during the last twenty years, and indeed it can be argued that by serving many exposure stations with one source, manufacturing with synchrotron radiation will be economically competitive (Ref. 7.2). If one synchrotron source serves 24 stations, then the cost per station will be about $1 million--less than the estimated cost of the projection optics of a competitive deep ultraviolet (DUV) stepper.

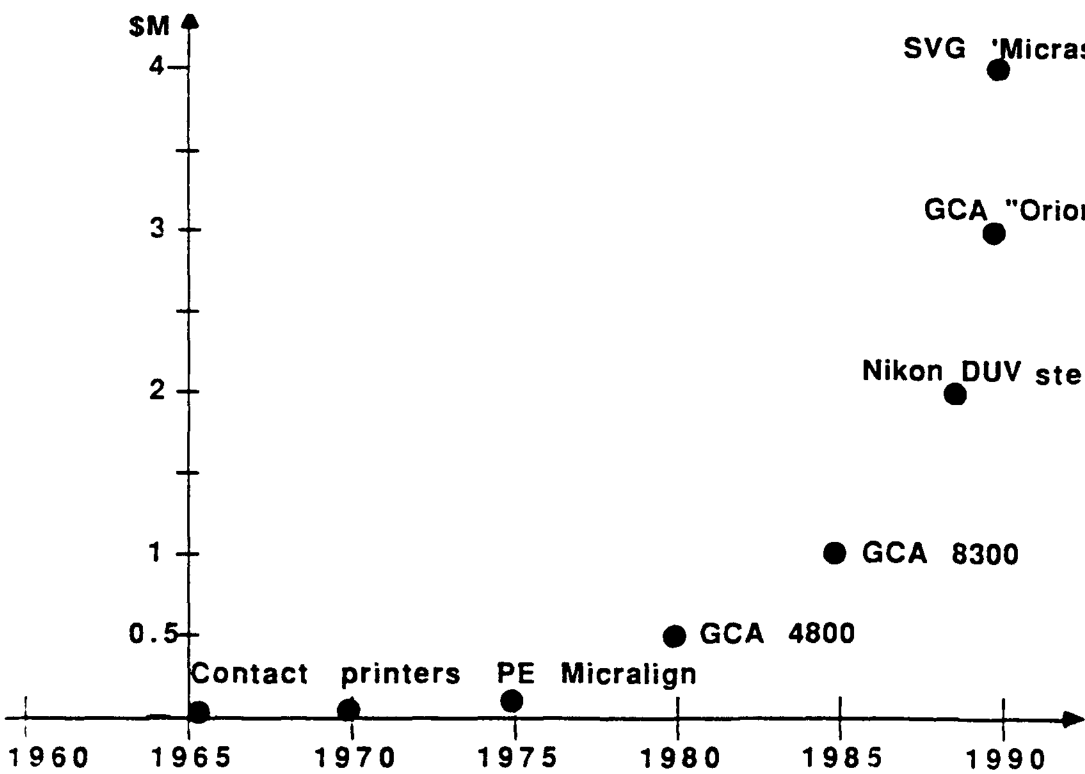


Figure 7.1. Cost of Wafer Exposure Tool as a Function of Time

STRATEGIES FOR ACHIEVING SMALLER FEATURE SIZES

Strategies employing photons with wavelengths greater than 100 nm for which refracting, low-loss materials exist are termed "optical"; the term "suboptical" refers to particles with shorter wavelengths and includes ions and electrons.

Optical Strategies

Figure 7.2, taken from a paper by S. Anzai of Nikon in 1990 (Ref. 7.3), is a good view of how the mainstream stepper technology is progressing. The circles indicate what is possible with existing resist and mask technology; the squares and triangles indicate what is possible with improvements there, such as phase shifting masks and surface imaging resists. Note there is no mention of field size; so to accommodate the expected die sizes, some form of stitching or mechanical scanning might be necessary. Note also that the minimum critical dimension of 0.25 μm could be in manufacture in the late 1990s with this evolutionary scenario. All the optical systems are refractive and use a mask pattern that is larger than that on the wafer to reduce the difficulty in making the mask. The JTEC panel found in Japan no significant departure from the scenario of Fig. 7.2. The relevant research and development carried out there is aimed at this timetable.

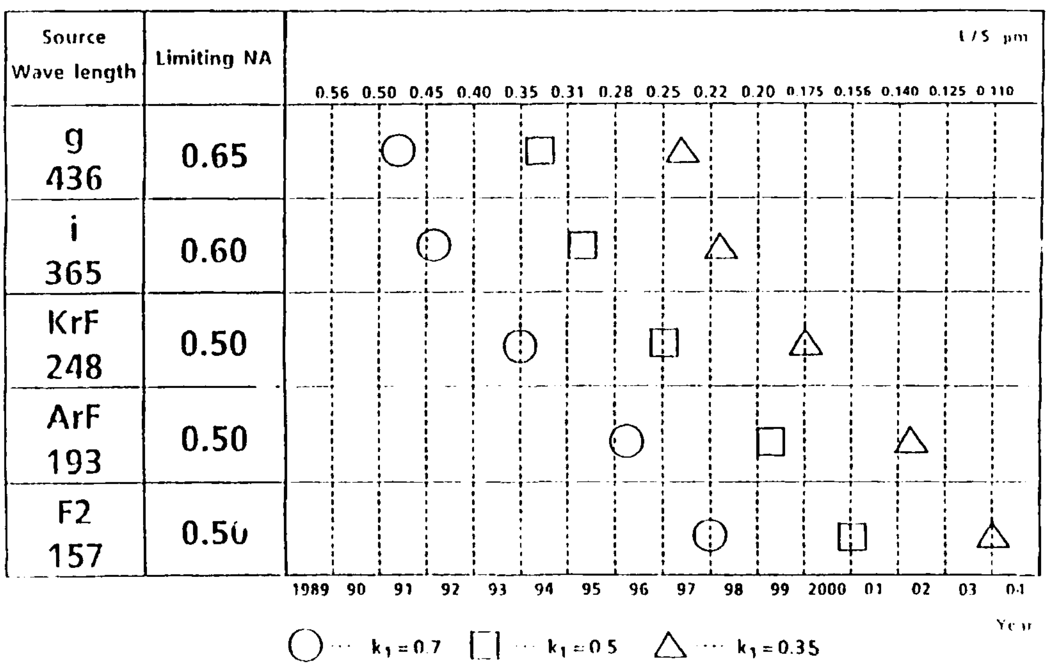


Figure 7.2. Minimum Half-Pitch as a Function of Time (after S. Anzai, Ref. 7.3)

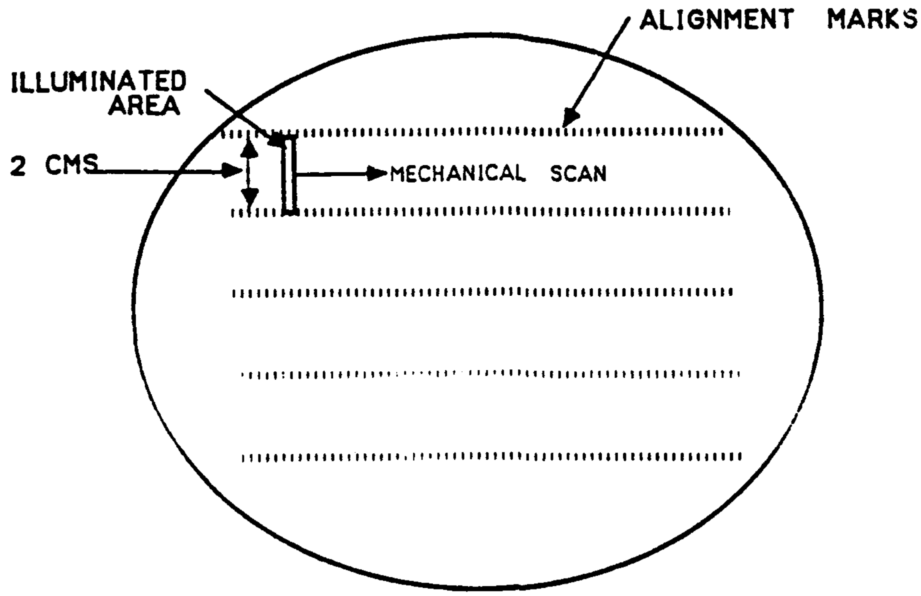
In the United States, this scenario is also the majority opinion. However, there are alternative strategies being pursued. The best known of these is the Silicon Valley Group's "Micrascan" (Ref. 7.4, Fig. 7.3) now being evaluated at IBM and SEMATECH. It is expensive ($4 million or more) but has an enormous field of view (20 x 30 mm^2) due to the mechanical scanning approach; this should be extendable down to 0.25 μm through the use of 193-nm radiation. The projection optics has a magnification of 0.25 and is mostly reflective; the refracting elements are only for correction, and so a relatively wide bandwidth illumination can be used (e.g., an unnarrowed excimer laser or a filtered mercury arc).

The second alternative is pursued by Ultratech Stepper Corporation (UTS). It employs unity magnification optics based on the Dyson principle (Ref. 7.5). The focusing is mostly reflective at concentric surfaces; as a result, most aberration terms are identically zero and only three elements are required, compared with about twenty for reducing systems. The most recent version (Fig. 7.4) promises a most attractive combination of enormous field of view (17 x 35 mm^2) and a very high NA (0.7) that should allow features less than the wavelength to be delineated. At present the 24-nm line of a mercury arc lamp is employed.

Suboptical Strategies

Electron-beam direct write. Despite the overwhelming throughput disadvantage of being a serial process, the electron-beam direct-write approach is still alive. In Japan, Hitachi is developing a system dubbed "cell projection" in which a substantial number of pixels (e.g., all those in one DRAM cell) are exposed simultaneously (thus mitigating the throughput disadvantage) (Ref. 7.6). Early claims estimated that over fifty wafers could be exposed per hour. The panel found that companies outside of Hitachi were taking this approach seriously.

Obviously, feature sizes can be even smaller than 0.25 μm. However, electron-beam technology has proven in the past to be expensive to develop. One very important point is that if electron-beam technology can be developed to directly generate VLSIC patterns for direct write, then writing equivalent patterns for XRL and optical masks at unity magnification is also possible. Some may quibble that masks are more difficult, but this is arguable. Pfeiffer and his colleagues at IBM described a cell approach in 1978, but chose to develop variable-shaped beam systems. Both Hitachi and Japan Electron Optics Laboratory Inc. (JEOL) have a long and prestigious history of electron optical instrument development, and both seem committed to developing direct-write tools (Ref. 7.7). Their resources dwarf those of their U.S. commercial counterparts (ETEC, Inc. and Lepton, Inc. for e-beam lithography tools), although the results of the substantial program within IBM may be made commercially available.



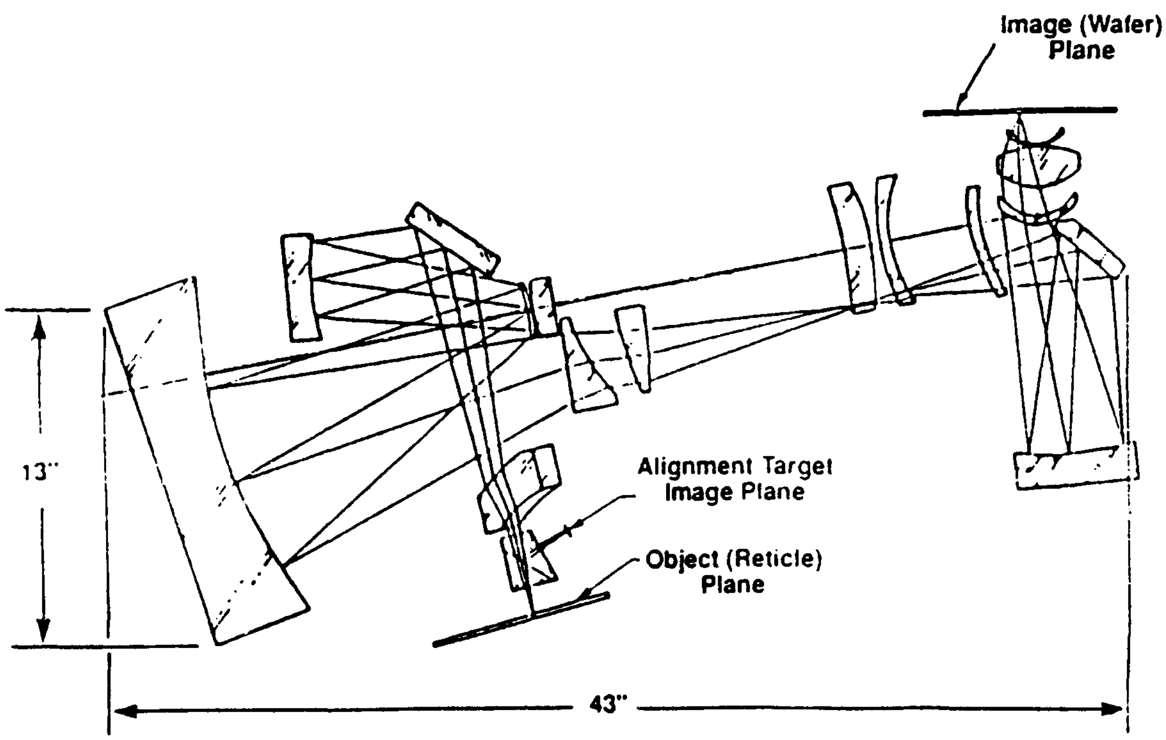


Figure 7.3. (a) Step and Scan Principle of the SVG "Micrascan"
(b) Projection Optics of the SVG "Micrascan"

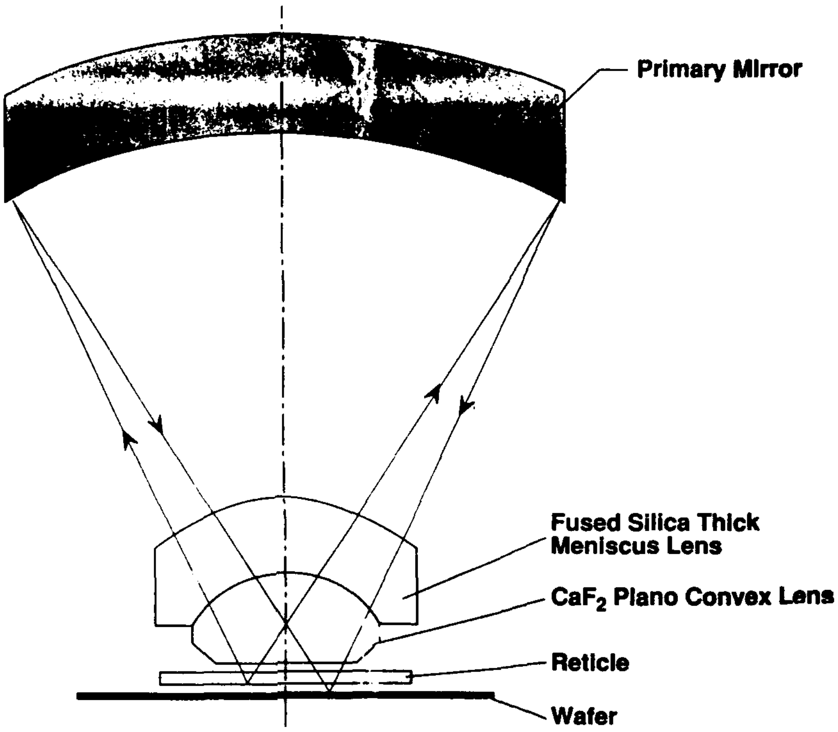


Figure 7.4. Projection Optics of the UTS Dyson System

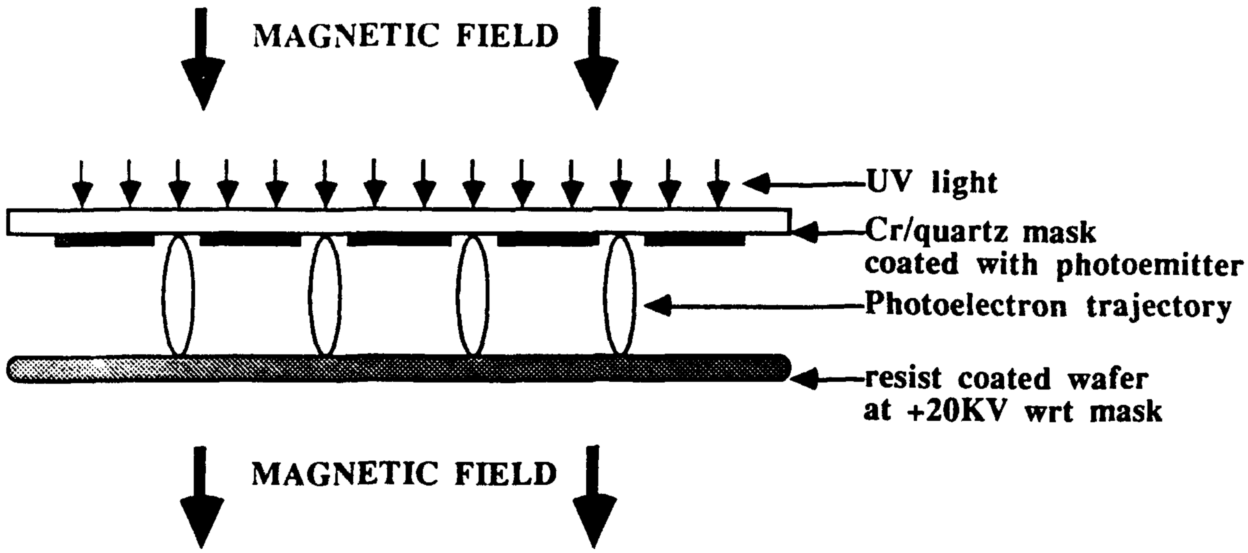


Figure 7.5. Schematic View of Cathode Projection System. Photoelectrons emitted from the clear areas of the mask are accelerated and focused by the combined electric and magnetic fields onto the resist coated wafer.

Masked ion-beam lithography (Refs. 7.8 & 7.9). There are two varieties of masked ion-beam lithography (MIBL): proximity printing and reduction projection printing. Proximity printing has the advantage that the mask substrate can be 100 nm silicon through which the ions channel, whereas for reduction projection printing, a stencil mask is needed to preserve monochromaticity.

The advantages of ion-beam exposure are the high sensitivity of resists and greatly reduced lateral scattering. The disadvantages include appreciable mask heating. The panel found no significant interest in Japan in either technique and consequent mask distortion.

Masked electron-beam lithography. Again, there are two varieties of masked electron-beam lithography, but in this case, both are unity magnification. The first type, cathode projection (Ref. 7.10, Fig. 7.5), was first demonstrated by Matta and his colleagues at Westinghouse in 1967 and was subsequently developed at Philips UK, Thomson CSF, and Toshiba. This approach has the advantage that a conventional UV mask can be employed. However, the resolution does not appear to be superior to that of steppers, and as far as the panel knows, it is not being developed at present.

The second type of masked electron-beam lithography, proximity printing through a stencil mask (Ref. 7.11, Fig. 7.6), was described by IBM (Sindelfingen). This approach has the outstanding advantage that mask distortion can be mapped and corrected for on-the-fly during exposure, so that the requirements for low spatial frequency distortion (e.g., runout) are greatly relaxed. It is not clear whether the mask technology will be adequate to make this approach attractive.

The panel found no interest in Japan in either type of masked electron beam lithography.

Reduction-projection electron-beam lithography. There has also been a little research in reduction-projection electron lithography. The first scheme employed stencil masks and 25 KeV electrons, but it does not seem to have been pursued since about 1980 (Ref. 7.12). The second, the subject of a quite recent paper (Ref. 7.13), employs 175 KeV electrons and a mask that uses a thin membrane substrate; a half pitch of about 0.25 μm was demonstrated.

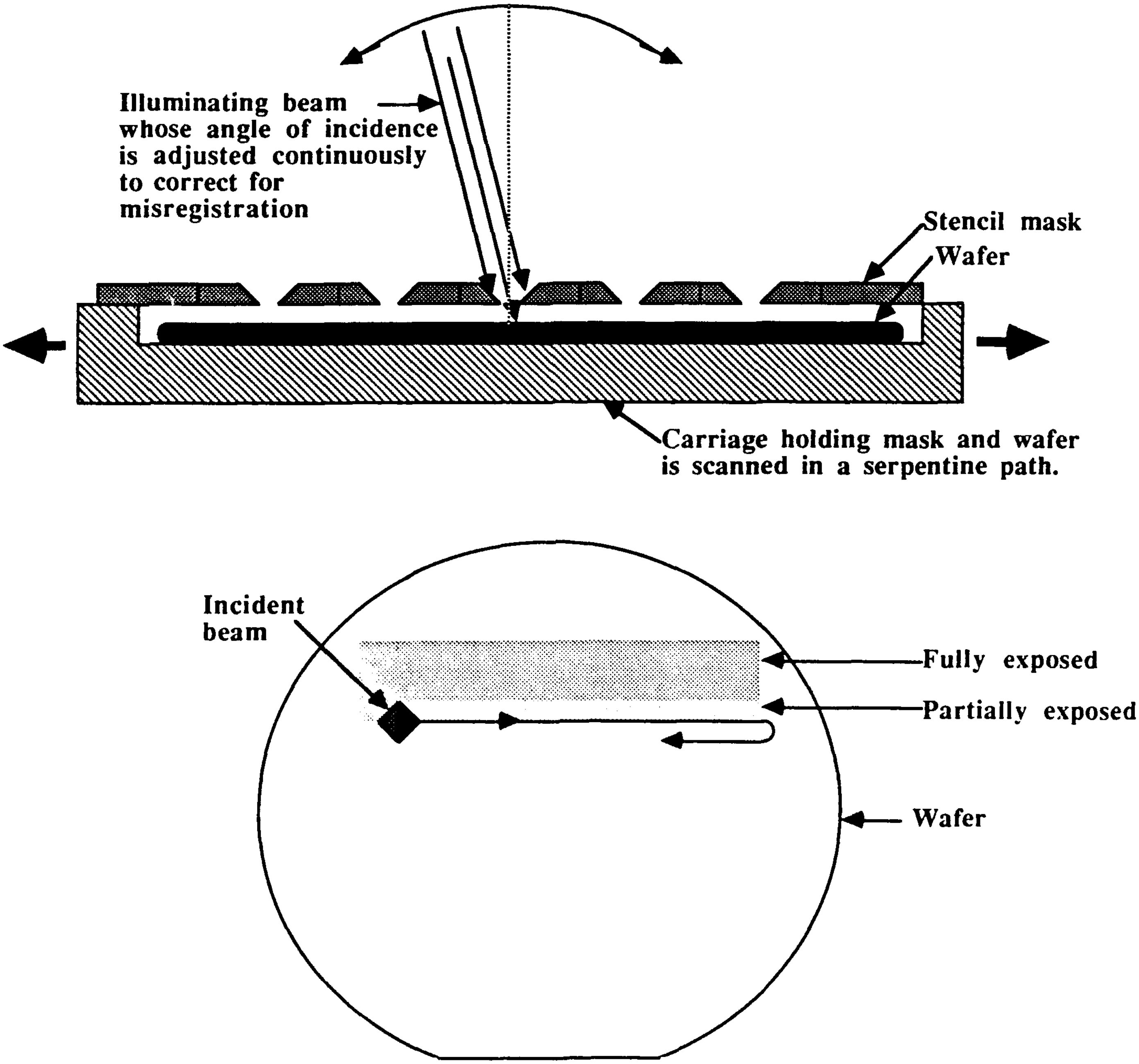


Figure 7.6. Electron-Beam Proximity Printer. Top view shows general arrangement. The mask and wafer are scanned through the diamond-shaped illumination as shown in the lower picture. The angle of incidence controls, by parallax, the offset of the landing position with respect to mask edge and hence can be used to correct for local misregistration. The scanning is arranged in the overlapping manner shown to minimize over- or under-exposure resulting from misplacement of the beam.

SUMMARY

Evolutionary refractive and reflective optical technology appears to be the main alternative envisaged for X-ray lithography for feature sizes down to less than 0.2 μm. Additionally, electron-beam direct-write strategy is being considered. In these two areas the Japanese efforts are impressive, both in research and development and in the resources being applied to developing optical steppers. Nikon has a complete laboratory devoted to investigating novel precision machining. It also has a small effort in X-ray optics that could have application in both lithography and, in the near future, microscopy.

Projections for the Future

The JTEC panel had few discussions with Japanese hosts about how to achieve a manufacturing technology with 0.1 μm minimum critical dimensions or about the equally interesting topic of how best to exploit such a manufacturing capability. The technical and financial challenges of achieving an economic 0.2 μm manufacturing technology leave the industrial concern over 0.1 μm problems several years in the future.

Key Researchers and Facilities

In addition to the people and places the panel visited to assess the status of X-ray lithography in Japan, it is also worth noting the work of the following individuals:

S. Namba and K. Gamo, University of Osaka: all aspects of electron-beam and ion-beam technology

T. Ohmi and T. Shibata, Tohoku University, Sendai: manufacturing deep-submicron ULSI circuits

Y. Hoiriike, University of Hiroshima: dry-etching processes and electron-beam lithography

N. Goto and others at JEOL: developing advanced electron-beam lithography tools

S. Hattori, Nagoya University

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APPENDICES

APPENDIX A: JTEC COMMITTEE MEMBERS WHO VISITED JAPAN

Team A		
	Dr. James T. Clemens AT&T Bell Laboratories	Panel Chairman
	Dr. Franco Cerrina University of Wisconsin	Panel Member
	Dr. Kenneth L. Davis Office of Naval Research	Committee Member
	Dr. Martin Peckerar Naval Research Laboratory	Committee Member
	Dr. R. Fabian Pease Stanford University	Panel Member
Team B		
	Mr. Robert W. Hill IBM Corporation	Panel Co-Chairman
	Dr. Gene E. Fuller Texas Instruments	Panel Member
	Dr. Henry I. Smith Mass. Inst. of Tech.	Panel Member
	Dr. David O. Patterson DARPA	Committee Member
	Dr. David J. Nagel Naval Research Laboratory	Committee Member
	Dr. Allen Lepore Army Electronics Laboratory	Committee Member
	Mr. Cecil Uyehara Uyehara International Assoc.	Consultant

APPENDIX B: LIST OF SITES VISITED BY THE JTEC COMMITTEE

APPENDIX C: PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

James T. Clemens (Chairman)

James T. Clemens is currently the Director of VLSI Research at AT&T Bell Laboratories.

After receiving his PhD in Nuclear Physics from the Polytechnic Institute of Brooklyn, NY, in 1969 he joined the AT&T Bell Laboratories in Allentown, PA. His principal assignment 1970-1980 was in the development and introduction to manufacture of VLSI Si-Gate MOS Integrated Circuit Technology. In 1980 he became head, CMOS Integrated Circuit Technology, and in 1984 the head of Advanced Lithographic Systems and Technology at AT&T Bell Laboratories at Murray Hill. He led the studies of fundamental issues associated with X-ray lithography, including a comprehensive analysis of boron nitride (BN) mask deformation due to stresses in the absorbing layer and synchrotron radiation damage. In 1990 he became the head of the VLSI Research Department, with responsibilities in SCRAM design, materials technology, advanced pattern transfer, multilevel metalization and the MH clean room supervision. Dr. Clemens is a Fellow of the IEEE for his contributions in VLSI physics. He has also studied management at the MIT Sloan School, studied Japanese language and culture for four years, visited Japan four times since 1987, and conducted a 3-1/2 month self-study during the summer of 1989 in the management of industrial Japanese microelectronics R&D as a research associate at the Research Center for Advanced Science and Technology, University of Tokyo, Komaba Campus.

Robert W. Hill (Co-Chairman)

Robert W. Hill is currently President of Hill Associates, Inc., a consulting firm.

Mr. Hill graduated from the University of Vermont in 1960 with a BS in electrical engineering. He joined IBM in Burlington in 1960 with the test engineering group. He was promoted to test engineering manager in 1963. He then held various engineering management positions in IBM manufacturing and development in Burlington, Vermont; Charlotte, North Carolina; and Fishkill, New York. Prior to leaving IBM in June, 1991, Mr. Hill was the functional manager responsible for the Advanced Lithography Systems development group at the GTD Advanced Technology Center in East Fishkill. His responsibilities included X-ray lithography, metrology, optical lithography, and resist development. He was also responsible for IBM's X-ray lithography program and facility.

Franco Cerrina

Franco Cerrina is currently a professor in the Department of Electrical and Computer Engineering at the University of Wisconsin, as well as Director of the Center for X-ray Lithography (CXrL).

Professor Cerrina received his PhD (Physics) from the University of Rome, Italy, in 1974. In his current capacity as Director of the Center for X-ray Lithography he supervises a staff of ten technical engineers in the area of beamline development. CXrL has four beamlines for XRL, 900 square feet of clean rooms, exposure systems (SVG step and repeat, 0.25 mm), inspection (FEOL 848), and processing. He has made personal contributions in the areas of X-ray optics, modelling (SHADOW program), X-ray microscopy, and surface physics. He is the author of over 60 papers, and holds one patent on SRL beamlines. He joined the Electrical and Computer Engineering department at the University of Wisconsin, Madison in 1984. He is a full professor.

Gene E. Fuller

Gene E. Fuller recently returned to Texas Instruments from a two-year assignment to SEMATECH.

Dr. Fuller received a BS in Physics from Michigan State University in 1969 and an MS and PhD in Solid State Physics in 1970 and 1973, respectively, from the University of Wisconsin, Madison. From 1973 to 1979 he was a member of the scientific staff at Brookhaven National Laboratory working on radiation damage and defect spectroscopy in crystalline materials and silicon dioxide. In 1979 he joined Texas Instruments as a member of the technical staff in the Houston Process Development Laboratory. In 1982 he moved to Dallas to join the Semiconductor Process and Design Center, where he was the Branch Manager for Advanced Lithography, responsible for development programs in X-ray lithography, e-beam lithography, and optical lithography. In 1987 he became the Director of the Manufacturing Science and Technology Project at Texas Instruments. In March 1989 he became a Texas Instruments assignee to SEMATECH. At SEMATECH he served as Manager of the Lithography Department.

R. Fabian Pease

R. Fabian Pease is currently a professor of Electrical Engineering at Stanford University.

Professor Pease received his BA, MA, and PhD degrees in Natural Sciences and Electrical Engineering from Cambridge University. From 1964 to 1967 he was Assistant Professor of Electrical Engineering at the University of California at Berkeley. From 1967 to 1978 he was at Bell Laboratories where he worked first on digital television and later on electron-beam and X-ray lithography. Since 1978 he has been Professor of Electrical Engineering at Stanford University where his areas of research include electron, X-ray, and deep ultraviolet lithography; LC-focused ion-beam technology; and system-level packaging.

Henry I. Smith

Henry I. Smith is currently a professor of Electrical Engineering at the Massachusetts Institute of Technology, and Director of the Submicron Structures Laboratory.

He received his PhD (Physics) in 1966 from Boston College. Professor Smith began his work on X-ray lithography in 1969, is coinventor of the basic X-ray lithography patents, and coauthor of the original papers in 1972. He and his coworkers have made contributions to several aspects of X-ray technology and applications, most recently in fabricating sub-100 nm electronic and quantum-effect devices. Professor Smith holds the Joseph F. and Nancy P. Keithley Chair in Electrical Engineering at MIT. He is a Fellow of the IEEE and a member of the National Academy of Engineering.

APPENDIX D: PROFESSIONAL EXPERIENCE OF OTHER COMMITTEE MEMBERS

Kenneth L. Davis

Kenneth L. Davis is currently Director of the Electronics Division at the Office of Naval Research.

Dr. Davis received his BS in physics in 1969 from Iowa State University, and received both his MS in physics (1971) and his PhD in electrical engineering (1973) from Purdue University. From 1973-1983 he worked at the Naval Research Laboratory (NRL) performing basic and applied research primarily in the area of surface acoustic wave devices. In 1981 he was appointed head of the NRL Electronics Technology Division's High Speed Components Section. Since 1983 he has been Director of the Office of Naval Research Electronics Division, responsible for a basic research program which encompasses the areas of solid-state devices and circuits, information systems theory, electromagnetics, and electronic environment of the ionosphere. More than 350 research grants/contracts are initiated each year from the Electronics Division to university (85%), industry (10%), and government (5%) laboratories. In 1988 Dr. Davis was selected to participate in the President's Commission on Executive Exchange program, where he spent one year working for Motorola's Corporate Director of R&D. Dr. Davis has authored or coauthored 28 publications and technical reports, 24 symposium presentations (9 invited), and 6 patents. He is a Senior Member of IEEE.

Allen Lepore

Allen Lepore is currently working at the U.S. Army Electronic Technology and Devices Laboratory at Fort Monmouth, NJ. His activities are centered on research in high-speed microwave modulation-doped field-effect transistors (MODFETs) and novel quantum electronic and photonic devices.

Dr. Lepore received his PhD in Electrical Engineering/Electrophysics from Cornell University in 1988. His thesis work was based on the design, fabrication, and testing of high-speed AlGaAs/GaAs MODFETs using high-resolution electron-beam lithography. This work resulted in the fabrication of the world's fastest 0.1 μm T-gate AlGaAs/GaAs MODFET and was also the first MODFET result with a unity current gain cutoff frequency in excess of 100 GHz. From 1988 to 1989 he was employed by Siemens Corporate Research where he continued research in microwave MODFETs based on AlGaAs/InGaAs/GaAs.

David J. Nagel

David J. Nagel is currently Superintendent of the Condensed Matter & Radiation Services Division of the Naval Research Laboratory (NRL).

Dr. Nagel graduated from the University of Notre Dame in 1960 with a BS in Engineering Science, and did his graduate work at the University of Maryland (MS in physics, 1969, and PhD in Engineering Materials, 1977). During active duty with the Navy, he was Navigator on the USS Arneb on Operation Deepfreeze (1960-62). Since joining the technical staff of NRL in 1964, he has held positions as a research physicist, section head, and branch head. Dr. Nagel's research interests center on X-ray physics, especially spectroscopy, with applications to materials analysis and plasma diagnostics. He has been active in development of plasma sources for microcircuit production with X-ray lithography. In his current position, Dr. Nagel manages the experimental and theoretical research and development efforts of 140 government and contractor personnel. Dr. Nagel has written or coauthored over 100 technical articles, reports, book chapters, and encyclopedia articles.

David O. Patterson

David O. Patterson is currently Program Manager for Advanced Lithography with the Defense Advanced Research Projects Agency (DARPA/MTO).

Dr. Patterson received his BS degree in Engineering Physics in 1962 and his PhD in Solid State Physics in 1966, both from the University of Tennessee. While at the University of Tennessee he was associated with programs in solid-state physics and high-energy physics at the Oak Ridge National Laboratory. He has worked at Harris Semiconductor and Texas Instruments, where he was responsible for device and process developments for MOS integrated circuits, and at the Naval Research Laboratory, where he directed the Research Devices Facility in fabrication of a wide variety of solid-state devices and did research in radiation hardening of advanced MOS integrated circuits. Dr. Patterson has managed the X-ray Lithography department at DARPA since its inception in 1987. He helped initiate the High Definition Displays program at DARPA in 1988. He was heavily involved with the Very High Speed Integrated Circuit (VHSIC) Program, serving as the Deputy Director for Submicron Technology. He played a key role in all areas related to VHSIC manufacturing technology, semiconductor devices and processing, optical and e-beam lithography, materials, packaging, and technology insertion. In his current position, Dr. Patterson is developing tools, materials, and processing required for advanced semiconductor manufacturing in the late 1990s.

Martin C. Peckerar

Martin C. Peckerar is currently in charge of nano-electronics process development at the Naval Research Laboratory.

Dr. Peckerar received his BS (Physics) in 1968 from State University of New York at Stony Brook, and his MS (Physics, 1971) and PhD (Materials Science, 1976) from the University of Maryland. In addition to his position at the NRL, Dr. Peckerar is also a part-time professor of Electrical Engineering at the University of Maryland. He is coauthor of the textbook *Electronic Materials: Science and Technology* (with S. P. Murarka, Academic Press, 1989) and coinventor (with D. J. Nagel) of the high-brightness laser-plasma source for X-ray lithography.

APPENDIX E: TRIP SITE REPORTS

Site Visited:	**NEC Tsukuba Research Laboratories**
Submitted by:	F. Pease M. Peckerar
Date Visited:	October 29, 1990
Persons Contacted:	Yuji Okuto Chief Engineer Research and Development Group
	Katsumi Suzuki Research Mgr., Semiconductor Res. Lab. Fundamental Research Lab.
	Hisatune Watanabe General Mgr. Fundamental Research Lab.
	Roy Lang Asst. General Mgr. Fundamental Research Lab.
	Toyomi Kanemaru Engineering Mgr. Mask Department LSI Manufacturing Division
	Junji Matui Research Fellow Research and Development Group

Funding

Total annual sales of NEC are ¥3444 billion ($22 billion). The visiting JTEC committee was told that product development costs and general research and development costs are about 10% of gross annual sales and that approximately 1% is spent on basic research. The corporate official statement is that ¥553 billion is expended on research and development annually.

Key Elements

NEC's activities in XRL are closely tied to SORTEC and to the KEK Photon Factory. There is approximately a six-man effort in XRL in the Tsukuba area, with the major effort devoted to maskmaking. In general, the technical activities are not centrally located in Tsukuba, but elements of the mask work are being performed in the Miyazaki Research Laboratory and the Sagamihara Research and Development Center.

NEC's main approach is to use SOR at about the 10 Å wavelength range with a gap of 20-30 μm. Researchers at NEC are also interested in long wavelength proximity printing techniques making use of the carbon K-edge for transmission. They are also interested in projection optics at the 44-50 Å wavelength range. There was apparently on-going experimental work in these areas at Tsukuba, but we did not have an opportunity to see these setups. Both approaches would use diamond membranes for masks. They stated that point source XRL systems may find limited application in the area of special devices, such as SAW transducers.

NEC staff believe that XRL offers the ability to yield low-cost lithographic technology for manufacturing at the 0.50 μm MCD and below, and they cited A. Wilson's paper (IBM cost analysis) in which XCRL was projected to reduce lithography cost by a factor of three. They appear to be trying to build a 16-Mbit DRAM with XRL but have not achieved a working device yet, although they stated that 0.50 μm testers have been produced. They have also demonstrated 0.20 μm features (Fig. NEC-1). They further stated that XRL may be used as early as 1996 in mass manufacture, but conceded that the 1998 time frame was more realistic.

NEC's current mask technology consists of silicon nitride membranes with tungsten absorbers. Researchers are also considering the use of silicon carbide as a membrane material. Masks are clearly high on the problem list; when pressed about the viability of 1X XRL masks they "had to believe." Overlay errors and defects are the chief problems. The use of optical reduction for generating such masks was being considered. They were relying on others to develop inspection and metrology for the masks, and a standards committee was being set up in collaboration with SEMI Japan and other companies. Another hurdle was the innate conservatism of the manufacturing engineers; this was more serious than financial outlay.

Staff at NEC feel that a low substate temperature etch is mandatory for minimizing feature undercutting. This is true both for ECR and for straight RIE etches. They have noticed changes in the ESR signature of SiN_x after 5-6 MJ/cm^3 absorbed. They are looking to SiC as a next-generation mask membrane material.

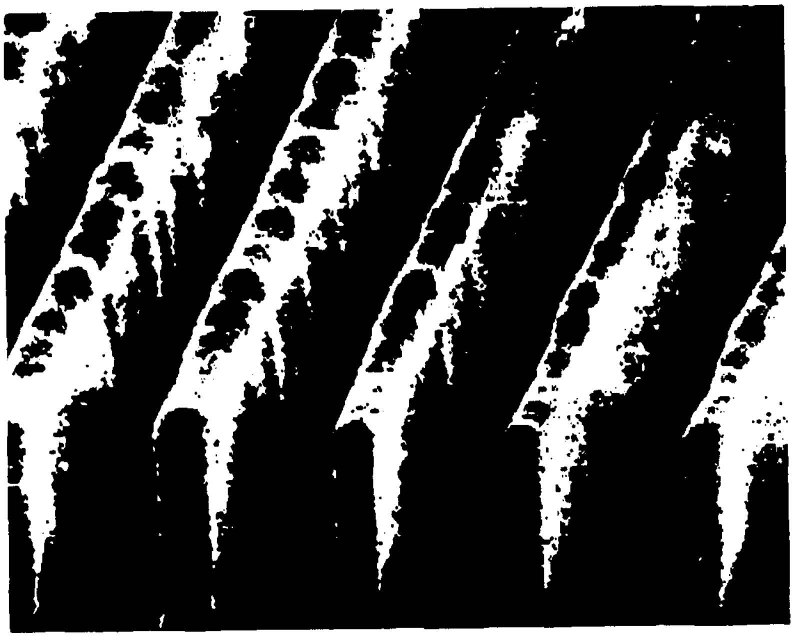

Fig. NEC-1. 0.2 μm resist features patterned by X-ray lithography using the NEC beamline at the Japan National Laboratory for High Energy Physics (reproduced with permission from the 1990 Annual Report of NEC)

General Comments

During the tour of the Tsukuba laboratory we were impressed by the very modern (1-year old) plant and by the fact that it is due to double in size within the next year. We were shown, among other things, a 4 Kbit memory employing superconductivity elements and a spectacular experiment (requiring a dedicated building) to study convection currents in growing 8-inch silicon crystals that employed X-ray viewing of 0.5 mm balls with a tungsten core and coated with SiO_2 to give neutral buoyancy in the molten silicon.

The overall impression is that, as expected, NEC is very professional in its approach to XRL. Its goals are conservative and it believes in working closely with SORTEC and other sources of SOR. It will be interesting to see when NEC succeeds in making a fully functional 16 Mbit DRAM using XRL for at least some levels. Other impressions given to us by our hosts are as follows:

- They feel alignment will be a bigger problem than low-defect mask making.

- They favor optical generation of daughter masks.

- They have no immediate programs planned in X-ray mask inspection and repair, but they feel low-voltage e-beam will be the inspection method of choice.

- A mask standards program exists in Japan, coordinated by SEMI/Japan.

- 0.15 μm design rules should be possible with a 20 μm gap.

- 1X lithography is difficult but can be achieved. The major insertion barrier is the "cultural" change brought about by the shift to X rays.

- Chemically amplified resists are attractive but aren't stable enough yet for production. They prefer SAL 601 to Ray PF for adhesion purposes.

- They feel that X-ray point sources have no place in VLSI production due to problems in boundary positioning.

- There may be a market for point sources and for existing X-ray equipment in low-volume market like lasers (for grating definition).

- They have worked with the Photon Factory to design a SiC mirror box for step-and-scan approaches to proximity printing. The beamline they designed is 72% transmissive to SOR X rays.

Site Visited: **IHI LUNA (at Tsuchiura near Tsukuba)**

Submitted by: D. Nagel

Date Visited: October 29, 1990

Persons Contacted: Yuichi Hoshi
Manager, Accelerator Project Group

Shinichi Mandai
Deputy Manager, Advanced Technology Development Department

Tamiro Nakashizu
Manager, Accelerator Project Group

IHI (Ishikawajima-Harima Heavy Industries Co.) is building a prototype storage ring for lithography called LUNA (Lithography Use New Accelerator), which it hopes to sell for semiconductor production in the mid-1990s. The company is well established (1853) and large ($6 billion/year), noteworthy for its large-scale products (e.g., ships) and diversity (six major areas, including production of jet engines and space systems). The LUNA project grew out of IHI capabilities for welding that were extensively employed for the past dozen years to produce vacuum and other systems for high-energy physics. In 1987, IHI did a preliminary design for the 8 GeV synchrotron x-radiation facility that will be built in Harima by 1997.

The warm magnet prototype LUNA has been designed and constructed over the past two years. Interestingly, IHI designed its own LINAC and RF systems. Ring assembly commenced in April 1989 and first beam in December 1989. The ring has 45 MeV (LINAC) injection and 800 MeV operation (21.8 Å critical wavelength). Current now is 15 mA (one-hour lifetime) with a goal of 50 mA. Full performance is expected March 1990. Twenty people work on the prototype, which cost $16 million. IHI believes semiconductor manufacturers will require ring costs below $8 million.

The lithography beamline (scanning mirror) is designed and now being procured with a stepper (from where was not said) for June 1991 installation and initial exposures in October 1991.

IHI touts the simplicity (reliability) and low cost of its ring as major advantages. The warm magnet design costs 60% of a cold magnet ring to build, although operating costs (electricity) will be higher for the warm ring. Size is a drawback. The major technical risk is low-energy injection (ramp time is only 1 minute). IHI does not have a projection now of how many ramp cycles will be needed to reach consistent and confident machine operation.

IHI expects to sell a production-design warm ring for semiconductor R&D by 1996 or earlier. It would have LINAC injection (from below), 5 ports for every 90° bend magnet (hence, up to 20 steppers) and (still) 50 mA. Two years will be needed from receipt of order to operation at the customer's site (including two-month assembly and six-month commissioning). IHI expects its ring(s) to be in use when mass production of chips by X-ray lithography begins in Japan in 1998 (256 Mbit DRAM).

IHI is also designing a cold ring, presumably to keep open its options. Mention of liquid nitrogen was made, so it may be anticipating high-temperature superconductor coils on an appropriate time scale.

Overall, IHI has positioned itself (with no government involvement) to be a prime supplier of at least warm storage rings for X-ray lithography.

Site Visited: **SORTEC**

Submitted by: F. Cerrina

Date Visited: October 29, 1990

Persons Contacted:

Dr. Nobufumi Atoda
Director
Research Laboratory

Dr. Koichi Okada
Group Leader
Synchrotron Radiation Application Department
Research Laboratory

Takeishi Kishimoto
Manager
Synchrotron Radiation Source Department
Research Laboratory

Masanobu Kodaira
Chief Researcher
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Research Laboratory

Kenzo Yanagida
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Kouichi Hara
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Naoki Awaji
Chief Researcher
Synchrotron Radiation Source Department
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Keisuke Koga
Researcher
Synchrotron Radiation Application Department
Research Laboratory

We were greeted by Dr. K. Okada at the door. He introduced Dr. N. Atoda, current laboratory director. After proceeding to a small meeting room, Dr. Atoda presented a brief history of SORTEC. The summary is contained in the appended "Outline of SORTEC" document. Briefly, Dr. Atoda explained that because XRL development was seen as too risky for single companies because of high costs, SORTEC was established in 1986 with a $100 million budget for a 10-year plan. The fund was established in part by MITI and MPT (through the Japan Key Technology Center) and by the 13 other member companies.[1] The development plan contains three items: (1) source; (2) beamline; and, (3) stepper.

Dr. Atoda summarized the status of the ring: 200 mA, and 1 GeV, 13 hours 1/e lifetime at 200 mA. (Note: these results are excellent and extremely impressive considering it took less than 4 years.) Dr. Atoda specified that the booster synchrotron is made by Toshiba, while Mitsubishi Electric built the LINAC and the electron storage ring. A period of questions and answers followed trying to clarify the relationship between MITI and SORTEC. It emerged that:

a. The Key Technology Center made the decision to promote the cooperative effort but the member companies formed the plan

b. The Key Technology Center is an administrative organization

c. The issue of intellectual property is defined on a case-by-case basis

The SORTEC staff is 34 employees, of which more than 20 are researchers. The rotation period is 2-3 years. A permanent staff exists (about 7 people). Our hosts felt that the rotation system was "not so good." During assignment to SORTEC, staff reporting structure is to SORTEC (no private reports to mother company). All experiments are performed at SORTEC, except where specifically required by lack of structure (example: resist support, mask distortions measurements).

After the introduction, we had a 1-hour tour of the laboratory, during which we saw many details. The aligner, which was built by Matsushita, was contained in a sealed helium environment; thus, we were not able to examine it in detail. We visited the control room, rings, and stepper.

a) Control room. This was well organized and cleanly laid out. All the standard systems were in place (beam monitors, current recording, etc.). We were told by Dr. N. Awaji (Chief Researcher, SOR) that the ring is quite flexible and that the beam existence is controlled in the limits of 0.1-5 mm-mrad, 0.5 being a typical value. The SORTEC staff can work now in top-off mode, thus keeping the current

[1] The Japan Key Technology Center is considered to be a member of SORTEC as well, bringing the total number of member organizations to 14.

constant to within one percent. They have a vivid graphics display of the ring and beamline status.

b) Rings. There are ? subsystems: injector, booster synchrotron, and storage ring. All the facilities are in a spacious building extending two floors underground. The injector is a short, 40 MeV LINAC that injects the 1 GeV booster synchrotron. The design appears clean and well implemented, with good equipment but without unnecessary frills. For example, the ion pumps were well spaced. The synchrotron was similarly well assembled (by Toshiba). The magnets are standard Fe-Si layered construction, with the vacuum tank being a thin-walled stainless steel corrugated pipe (to cut the Eddy currents). A transport line connects the booster synchrotron to the storage. The shielding around the synchrotron appears light, probably because of the non-occupancy during normal operation. The ring itself elicits the same comments; the electronics are neatly packaged at the ring center.

c) Steppers. The rings are in a normal lab environment. We passed two air showers before being admitted at the stepper location. The Matsushita (Panasonic) stepper can be operated in moderate vacuum or atmosphere. The sturdy tank is connected to the beamline with large (6") bellows. The tank is mounted on an air isolation system. The stepper description and results have been reported to the EIPB '90 conference, but the researchers were quite willing to discuss their results and approaches. We were shown two X-ray masks, usual 3" SiN/Ta mounted on 150 mm^2 glass plates (5 mm thick). The plates were held by vacuum clamping in 4 positions on a piezo driven table. The wafer was held on a vacuum chuck and the stepper is capable of cassette to cassette operation. It can also load a 4-mask cassette. The gap is settable in the 10-50 μm range. Main limitations are wafer planarity (1-2 μm after chucking) and mask planarity (5-7 μm). This data caused some questions, since masks usually have better flatness.

Currently the stepper has slow alignment times. Its goal is to achieve 0.4 sec alignment but stepping can be 1-2 s (limited by air bearings). The stepper is under PC control (Intel-310 were common systems). A helium closed circuit system keeps the temperature to +/- 0.2°C. The stepper alignment uses 10 DOF.

We spent about half an hour at the stepper. We were shown accessory equipment (JEOL JEPAS [a linewidth measuring system], Hitachi S900 [SEM], PE DRM9000, various resist processing) of excellent quality. The other beamlines are used for

1. Mask damage, UHV/controlled atmosphere
2. Description studies
3. Unclear -- various experiments for spectroscopy/mask characterization

After returning to the meeting room, a long question and answer session followed (from 4:15 to 5:30). J. Clemens and M. Peckerar gave a brief description of the U.S. program. The salient points made by our hosts were as follows:

1. Future of XRL -- various answers, no one clear cut. General feeling that XRL would become viable at 0.25 μm.

2. Most SORTEC staff people are from R & D rather than manufacturing, generally quite young and very upbeat.

3. Costs. Ring(s) are approximately ¥3.0 billion, approximately $24 million. They use 400 KW of power. The stepper is about ¥1.0 billion, or $8 million.

4. Major problem: overlay and mask. There was some confusion on the meaning of various terms. They see 5 main contributions to alignment: mask distortion, patterning, alignment, random defects, wafer warpage, and thermal control.

5. Resists are not a problem (consensus).

6. Next activities: process development (resists, mask characterization); maybe a second stepper; push ring to 500 mA to shorten exposure time.

7. Mask still seen as a SiN-based process.

<u>General remarks</u>

The laboratory is well set up and managed. The performances of the rings are SUPERB, especially if we consider that they have been achieved in three years. The SORTEC team is strong and they will go a long way in developing XRL.

There are 14 SORTEC member organizations: The Japan Key Technology Center, NEC, Matsushita, Hitachi, Sony, Nikon, Canon, Oki, Toshiba, Fujitsu, Mitsubishi, Sharp, Sanyo, and Sumitomo.

Attachment to SORTEC Site Report

Extract from

"OUTLINE OF SORTEC CORPORATION"

(handout provided to the JTEC team during its visit to SORTEC)

May 16, 1990

Background of Foundation

Synchrotron orbital radiation (SOR) is a kind of electromagnetic wave emitted from highly accelerated electrons when they are bent by magnetic fields. SOR is expected to be a useful X-ray source for micro-lithography because it has many attractive features such as high intensity, vertically narrow dispersion, virtually continuous wave, and so on.

However, X-ray lithography using SOR (SOR lithography) remained in a basic research stage, and it was beyond the economic investment as well as technical capability, provided by each corporation. Consequently, there had been a strong requirement for a foundation of co-operative R&D organization.

Based on the above mentioned background, SORTEC Corporation was established on June 3, 1986, financed by the Japan Key Technology Center and thirteen corporations.

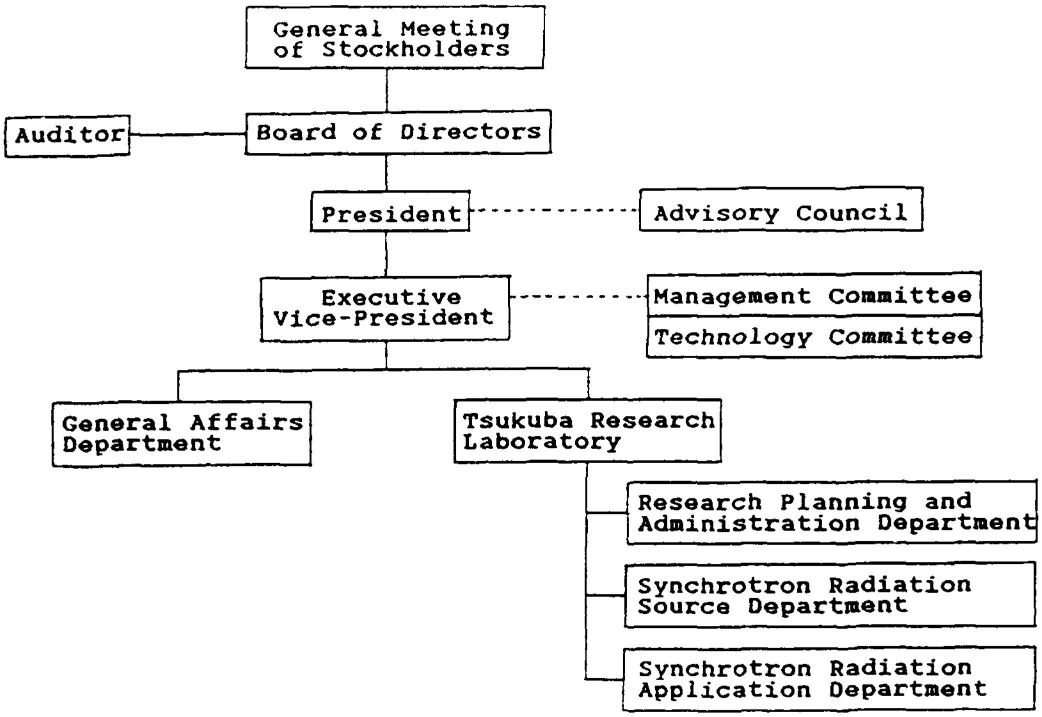
R & D Program

SORTEC is scheduled to perform the following R&D activities, under a budget of ¥14,300 million (about $100 million) for ten years.

1) SOR facility with stable and intense radiation,
2) Beamline with high transmittance for SOR,
3) Aligner with high accuracy for SOR lithography.

Until the middle of 1990, the SOR facility, beamlines, and the first aligner will be prepared. From then to the early part of 1997, ability tests and improvements of these facilities, and SOR lithography experiments will be conducted to develop key technologies for a quarter-micron level process.

Organization



Investors

The Japan Key Technology Center, Toshiba Corporation, NEC Corporation, Hitachi, Ltd., Fujitsu Limited, Matsushita Electric Industrial Co., Ltd., Mitsubishi Electric Corporation, Oki Electric Industry Co., Ltd., Sanyo Electric Co., Ltd., Sharp Corporation, Sumitomo Electric Industries, Ltd., Sony Corporation, Canon Inc., Nikon Corporation

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Site Visited: **Photon Factory (Tsukuba)**

Submitted by: D. Nagel

Date Visited: October 29, 1990

Persons Contacted: Professor J. Chikawa
Director
KEK Photon Facility, Tsukuba

Dr. Koso Mochiji
Hitachi
Senior Researcher
4th Department
Central Research Laboratory, Hitachi

Mr. Masaaki Itou
Hitachi
Researcher
Development Department
Central Research Laboratory, Hitachi

Mr. Tsuneyuki Haga
Research Engineer
Advanced Beam Technology Research Group
Manufacturing Systems Technology Laboratory
NTT LSI Laboratories

Mr. Tsutomu Mizota
Research Engineer
Advanced Beam Technology Research Group
Manufacturing Systems Technology Laboratory
NTT LSI Laboratories

The Photon Factory is the principal multipurpose synchrotron radiation facility in Japan. The comparable facility in the United States is the National Synchrotron Light Source at the Brookhaven National Laboratory. The Ministry of Education provides $20 million annually for operation (exclusive of scientists' salaries). The facility provides 3500 hours of light to users per year.

Four major Japanese companies have lithography beamlines at the Photon Factory: NTT (Beamline #1); Hitachi (Beamline #8); NEC (Beamline #9); Fujitsu (Beamline #17). These companies pay $400/hour for photons. They must provide their lines to general users for half of the available beam time. Tours are provided by Hitachi and NTT.

Four people work on the Hitachi lithography project. The company has three branch lines and four experiment stations on Beamline 8: (a) soft X-ray absorption and photoelectron spectroscopies, (b) extended X-ray absorption fine structure spectroscopy and (c) X-ray lithography or computed tomography.

The Hitachi lithography station employs two types of scanned mirrors. Superpolished fused SiO_2 coated with gold has produced dose uniformity to +/ 1% over a field 30 mm wide and 25 mm high. Diamond turned parabolic Cu substrates 50 cm long coated with Au are also used. The latter are oscillated vertically about 25 mm at 2 Hz to provide the exposure field. The exposure station is employed for resist and mask evaluation, with approximately 6 exposures per day. A vacuum environment is used now although this is unfavorable due to mask heating. Helium will probably be used in the future.

PMMA and RAY PF resists have been exposed by Hitachi. One micron of PMMA can be fully exposed in 20 sec. Little else about resists was presented.

Mask testing seems to be the major thrust on the Hitachi beamline, notably gold on silicon nitride membranes. Radiation damage tests up to 5 Kj/cm^2 were done (in about 6-hour exposures without scanning). If oxygen contamination of the nitride is kept below 1 atomic percent, radiation resistance was found to increase markedly.

NTT's beamline has two branches, one for proximity exposures and another for projection lithography research. Areas (10 mm^2) are exposed on the proximity line in PMMA and FBMG resists. The second line has two experimental stations. The forward station has a plane grating monochromator for measuring the energy and angle dependent reflectivity of multilayers. The end station is a large vacuum X-ray optical bench in which alternative geometries for reflection masks and reduction optics are tested with white radiation. Multilayer masks and two elements (e.g., Schwarzchild) optics are being used.

In general, the lithography work seen at the Photon Factory is research on important aspects of the overall lithography problem, largely beamline design, masks, and resists. Despite its industrial importance, the work has a clear academic flavor. None of the company's beamlines has a stepper, and no operating circuits have been made with X-ray lithography at the Photon Factory.

Company Visited: **Electrotechnical Laboratory, Tsukuba Center**

Submitted by: M. Peckerar

Date Visited: October 30, 1990

Persons Contacted: Dr. Toshio Tsurushima
Director
Electron Device Division

Dr. Masanori Komuro
Chief of Micro-Beam Section
Electron Devices Division

Toshihiko Kanayama
Process Technology Group

Dr. Takio Tomimasu
Chief of Synchrotron Laboratory

ETL is a government laboratory with a major development effort in synchrotron systems. The whole laboratory is funded at a level of $68 million per year and supports 675 people. Over the past ten years, five synchrotrons were constructed at this site; one of which is superconducting. The X-ray lithography research group is relatively small (< 5 people). Dr. Atoda, now head of the SCRTEC effort, was originally at ETL.

Major Program Elements

A. Synchrotron Design. Dr. Tomimasu has supervised the design of five rings, NIJI 1-4 and TERAS. All but NIJI-1 are still functioning. NIJI-3 uses superconducting magnets. Most rings are used in DUV and X-ray photochemical research. TERAS has an experimental beamline for X-ray lithography. He feels with some certainty that the ideal ring should employ conventional magnets. The "ideal" ring specifications are 800 MeV, 200 mA, 5 m radius (bending magnets 1.6 Tesla, 2 m bending radius). Production costs were as follows:

¥0.85 billion (approx. $6.2 million): ring construction
¥0.35 billion (approx. $2.5 million): linear injector
¥0.15 billion (approx. $1.1 million): aligners and litho stations (each)
¥0.28 billion (approx. $2.04 million): beamlines

If a superconducting ring is constructed, it should be a warm bore ring. The current approach of Dr. Tomimasu and his staff employs no X-ray mirror scanners: they prefer to perturb the orbit of the ring. The time from design to commissioning for his rings is 1-2 years.

B. Mask Development. Kanayama has done extensive work developing silicon nitride membranes. He has developed a reactive ion sputtering process which is oxygen free. He controls the stress in his membranes by adjusting the argon background pressure in his sputtering chamber. His films are near stoichiometric. WN_x absorbers (4000 A thick) are used. The stress in the absorber is controlled by 400 KeV N^+ or Ne implants. The final stress in the absorber is $< 2 \times 10^8$ dynes/cm^2 (compressive). He notes a radiation-induced feature placement shift of about 0.1 μm after 2×10^9 J/cm^3 are absorbed. Kanayama feels that stability can be achieved in crystalline and in polycrystalline films, but the glasses are inherently unstable. For defining features in the absorber, he and his staff have developed a novel Al_2O_3 masking technique.

C. Alignment. Kanayama and Atoda developed a heterodyne grating alignment scheme using three gratings, two on the mask and one on the wafer. A He-Ne beam is used. They claim alignment to better than +/- 0.05 um (point repositioning error). Mask making and alignment are the key issues that must be addressed before the technology can be inserted into the production line.

D. Diffraction-Limited Resolution. Kanayama has done extensive study of linewidth degradation as a function of gap. He and his staff have concluded that diffraction-limited resolution of 0.15 microns is possible with 10-15 micron gaps. Larger gaps can be used with feature sizing, but the process latitude is degraded. They have only worked in PMMA resists.

E. General Comments:

- The main purpose of the ETL program was to achieve a lithographic system with the DOF needed for 3-D ICs.
- ETL staff feel that the mask transmission dictates that the wavelength of choice is 10 Å.
- They have programs in X-ray mirrors and in plasma X-ray sources (not immediately related to the X-ray program).
- They would like to investigate applicability to quantum effect devices.

Site visited: **Canon Research Laboratory, Atsugi**

Submitted by: R. W. Hill

Date visited: October 30, 1990

Persons contacted:

Dr. Hajime Mitarai
Senior Managing Director

Mr. Ichiro Endo
Director

Mr. Kunio Watanabe
Senior General Manager

Mr. Hiroshi Hanada
Deputy Senior General Manager

Dr. Takao Utsumi
Deputy Senior General Manager

Mr. Yukichi Niwa
General Manager

Mr. Shunichi Uzawa
General Manager

Dr. Takao Yonehara
Manager

Mr. Tsuneaki Kadosawa
Manager

Mr. Keiji Suzuki
Assistant Manager

Canon, Inc., had revenues of $9.2 billion in 1989. It has a broad product line, which includes small computers and peripherals, office products, TV production equipment, cameras, and semiconductor optical production equipment. The semiconductor lithography portion of its business is about 5%, or approximately $450 million. It has facilities located in many areas of Japan, with its main research center being located at Atsugi.

Canon has been involved in X-ray lithography for three years in two areas: X-ray proximity printing aligners and projection X-ray lithography. These projects are funded solely by Canon with no government support and are presently staffed at a level of approximately fifty people.

There was little discussion on the projection X-ray printing project other than they have evaluated multilevel coatings using a beamline installed at the KEK facility at Tsukuba. Proximity X-ray printing aligners were discussed in some detail and a tour was given of the laboratory, which has two prototype tools in construction.

The aligner is relatively large and consists of a large tubular frame, inside of which is mounted a low pressure chamber containing the vertically mounted xy table, the mask and its mounting and transfer mechanism, a fine alignment system, and other necessary elements. The beamline will contain the mirror optics box, which is attached to the chamber. Two other units will be attached to the chamber: a mask loading system with a twenty reticle cassette, and a wafer cassette load/unload system. The wafer system is sized for 6-inch wafers.

The vertical table contains a flexure plate upon which the wafer chuck is mounted. Fine alignment is performed using the flexure plate, which is controlled by the alignment logic. The course xy drivers are cylinder-type actuators which comprise ball lead screws and DC motors. The mask is transferred into the tool via a transfer arm into its holder which is then positioned by piezoelectric transducers.

The system with the attached wafer and mask handler is evacuated, helium is introduced to bring the pressure back to 150 millitorr, and the wafer is exposed. Wafers and masks will be transferred automatically from their cassettes, after which the cassettes are removed and the cycle is repeated. The throughput is expected to be in the forty wafer per hour region.

The mirror is a fixed cylindrical mirror mounted ahead of the stepper in the beamline and is designed to expand the beam over a maximum 30 mm^2 field. The field shutters are adjustable in the tool.

Thermal design and management of the system is well engineered, and it is evident that Canon's optical aligner experience is being well utilized.

Two prototype systems now under construction will be complete in 1991. One will be installed at an unnamed location on a synchrotron where the necessary information will be gathered to make the aligner into a commercial unit.

There was little discussion of the beamline configuration. Canon will use the information gathered from this research to configure and produce commercial aligners.

Site Visited: **Electrotechnical Institute**
Quantum Radiation Division

Submitted by: F. Cerrina

Date Visited: October 30, 1990

Persons Contacted:

Dr. Hiroshi Kashiwagi
Director-General
Electrotechnical Laboratory

Dr. Takio Tomimasu
Director
Quantum Radiation Division

Katsuji Emura
Electromagnetic Application Systems R&D Department
Osaka Research Laboratories
Sumitomo Electric Industries, Ltd.

We met with Dr. Tomimasu at 2:00 pm after the morning visit to ETL and had a brief, but pleasant conversation with Dr. Kashiwagi. Tomimasu spent about 3 hours with us. Tomimasu began describing the facility of the Quantum Radiation Division. The facility houses all the sources which have been built by the division. The laboratory facility is on two floors. The first is above ground and houses the management room and the measurement control room. The rest of the building is underground so that all the X-ray sources are shielded by the dirt pile around the experimental chambers. The center part of the facility is the LINAC. The LINAC is capable of accelerating to about 300 MeV and serves as the main injector for the various rings that have been built at the center. The magnets for the LINAC were built by Mitsubishi Steel, while the quadrupoles are supplied by Mitsubishi Electric. There are four electron storage rings operational at ETL Quantum Radiation Division as of November, 1990. They are TERAS (Tsukuba Electron Ring for Accelerating and Storage) and three electro storage rings of the NIJI (Niji means rainbow in Japanese) series. They are NIJI-II, -III, and -IV. NIJI-I was a prototype built in 1988 for the study of low-level injection; it has been disassembled and replaced by NIJI-II. Each ring is housed in its own laboratory.

TERAS. The TERAS ring is the workhorse of the facility. First-beam storage was achieved in 1981 and the storage ring has been operating ever since for various applications to photoelectron spectroscopy, photometric standards, photo irradiation studies, solid-state physics, and in particular, X-ray lithography studies. TERAS is fairly similar to some of the U.S. rings (VUV ring at Brookhaven and

Aladdin in Wisconsin). The ring is an accelerating type, since the electrons are injected on the LINAC at 300 MeV and then are further accelerated to the operational energy of 800 MeV. Maximum current stored in the ring is on the order of 250 mA with a lifetime of several hours. The structure of the ring is fourfold symmetric with bending magnets and 4 triplets for beam focusing. It is interesting to note that the ring was designed in a year and assembled in about 10 months for a total cost of ¥250 million.

To the visitor, the ring appears as a well-designed and well-implemented system but with the characteristics of a research and development facility. That is, the efforts have clearly been concentrated on reaching a working ring in the fastest time and at the lowest possible cost rather than in the development of a product suitable for commercialization. The transfer of technology to a manufacturer's production facility will require a considerable engineering hardening of the design.

The operation of the ring has been very successful with very high up-time and excellent performance. Of particular interest to the panel was the beamline implemented for X-ray lithography studies because the researchers of ETL decided to implement a beam-scanning system. In X-ray lithography it is necessary to spread the horizontal fan of radiation into the whole field of exposure. This can be achieved in several ways (rastering mask and wafer together across the beam, scanning the X-ray beam by using an optical mirror, oscillating the electron-beam): ETL chooses to implement the electron beam scanning system. When an electron is accelerated in a magnet field the radiation is emitted in the plane defined by the orbit of the electron. If this plane is oscillated, the radiation will follow the movement of the orbit plane; it is then possible to oscillate the electron beam to have an oscillating fan of radiation at the sample position. The method was successfully implemented at TERAS for the X-ray lithography beamline. There are several advantages to this method since it does not require the use of any optical system or mechanical system to spread the radiation; however, it is difficult to use such a method in a system shared by many users because of the perturbations on the orbits that are created by the oscillation of the beam.

NIJI-I / NIJI-II. These rings have been built as prototypes and study cases for the construction of the superconducting storage ring NIJI-III. The design study of NIJI-I began in 1984 and was completed in 1986. The ring was a small size conventional magnet and was intended to study the injection into low-energy machines. NIJI-I was able to store up to 500 mA of 160 MeV electrons with a lifetime of about 70 minutes. These data are very important because they demonstrate the possibility of storing large amounts of current on low energy. The ring was shut down and disassembled in March 1989. It was replaced by NIJI-II as a prototype for the construction of the superconducting ring. The maximum current stored in NIJI-II was 120 mA and it is considered completed at this time. It is important to notice that the NIJI series has been built in collaboration between

Sumitomo Electric and ETL. Two undulators are installed on NIJI-II, one for CVD experiments and the other for elliptical radiation sources. At the moment no beamlines are installed on this ring.

NIJI-III. NIJI-III is a superconducting, relatively compact storage ring. It has a cold bore and can undulate the beam in order to define a large exposure area as discussed above. The machine was also constructed by Sumitomo Electric in collaboration with ETL, and after the initial period of studies, it will be shipped to the Sumitomo Electric plant where it will be outfitted with a beamline and will be used for X-ray lithography applications. Dr. Tomimasu expected this to happen in the early part of 1991. The machine is the cold bore type; that is, the vacuum ring itself is at liquid helium temperature. Dr. Tomimasu commented that a leak caused a long down time because of the cold walls. The machine can be injected quickly and then accelerates the electrons to the operating energy. It takes on the order of 20 minutes for an injection cycle. The lifetime is of several hours. The design of this superconducting storage ring is different from the usual ones, which are based on an oval racetrack design. In summary, the ring is operational and will be soon transferred to Sumitomo Electric.

NIJI-IV. This is a long straight-section ring designed to house a free-electron laser. It was under assembly and it is expected to be operational in 1991.

Stepper and XRL at ETL. The stepper was designed and built at ETL. It is a single-stage system using a vacuum platen to load the wafer and/or the mask. The masks themselves were also produced at ETL, using the SiN approach but with a different twist. They were deposited by sputtering from a Si target in $Ar+N_2$ atmosphere. After deposition the W (tungsten) films were patterned using a thin Al_2O_3 layer as a resist. Radiation damage was observed by using the stage interferometer as an in-line measuring tool. The stepper was clearly intended for technology demonstration rather than production. The masks did reflect the type of scanning (beam wobbling), being 5 (V) x 20 (H) mm². The Be (beryllium) window of the beamline was 5 (V) x 20 (H) mm² and 25 μm thick (full He (helium) pressure exposure). Typical exposures time in PMMA were 1 minute with beam at 700 MeV and 100 mA. ETL/QRD will keep using the stepper for producing small runs of III-V materials.

General Considerations

QRD has impressive machine building skills. Dr. Tomimasu is certainly an international figure in this arena. He and his staff have developed a large reserve of know-how (and parts!) so that it is very easy for the lab to design, assemble, and qualify a new electron ring. In the United States we do not have anything comparable, no matter what meter we wish to use: achievements, or cost-effectiveness.

Table ETL-1
Properties of ETL's Electron Storage Rings

	Type[a]	Energy (GeV)	Current (mA)	Applic	E_c (eV)	Size (μm)	Status
TERAS	RT	0.8	250	Gen	568	10	Up
NIJI-I	RT	0.27	524	Exp	62	4	Off
NIJI-II	RT	0.6	120	Exp	342	4x6	Up
NIJI-III	SC	0.62	120	XRL	1057	4x5	Up
NIJI-IV	RT	0.5	-	FEL	231	4x12	Cnstr

[a] RT = room temperature; SC = superconducting

Site Visited:	**NTT LSI Laboratories, Atsugi**
Submitted by:	G. Fuller
Date Visited:	October 30, 1990
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	Dr. Hideo Yoshihara Project Team Leader and Executive Research Engineer
	Dr. Teruo Hosokawa Senior Research Engineer and Supervisor
	Mr. Sunao Ishihara Senior Research Engineer and Supervisor
	Mr. Hiroo Kinoshita Senior Research Engineer and Supervisor
	Mr. Takeshi Kaneko Senior Research Engineer
	Mr. Kimiyoshi Deguchi Senior Research Engineer
	Mr. Tsutomo Mizota Research Engineer
	Mr. Tsuneyuki Haga Research Engineer

NTT was founded in 1891 and is the dominant telecommunications organization in Japan. Today NTT has over 52 million telephone subscribers and is heavily involved in a wide variety of advanced communication and information technologies.

NTT has six research facilities. The NTT research laboratories can be viewed as analogous to Bell Labs of about 10 years ago (pre-breakup of AT&T). That is, their efforts are in the national service as well as aimed at producing what NTT needs as a company. There are 7,000 researchers at NTT, with over $2 billion being spent annually on research at numerous centers primarily in the general vicinity of Tokyo. The Atsugi R&D Center consists of the LSI Laboratories and the Optoelectronic Laboratories. The LSI Laboratory has about 400 research workers.

NTT is the pioneer in the study of X-ray lithography in Japan, having started work in 1974. Over the years, NTT research in XRL has involved conventional electron bombardment sources, discharge plasma sources, and SOR sources. At the present time, all the work is centered around the two SOR sources installed and operating at the Atsugi site. The JTEC team was told that research work on the discharge plasma source had stopped at NTT in 1988. This technology was transferred to Nichicon Ltd, and the plasma source is commercialized.

The NTT program is a complete XRL effort from the source through IC device fabrication. More than 20 people are working on the program.

The two SOR rings are

1. NAR (Normal-conducting Accelerator Ring), which is 52 meters in circumference and operates at 800 MeV

2. Super-ALIS (Superconducting Atsugi Lithographic SOR), which is a superconducting magnet ring operating at 600 MeV.

Both rings receive injection from a 15 MeV LINAC.

The NAR was designed by NTT and manufactured by Toshiba. It currently has four beamlines complete or in construction. Three beamlines are currently in operation. One line supports the NTT-built stepper and the bulk of the NTT XRL patterning effort at this time. A class 1000 clean room encloses the outer end of the beamline.

The Super-ALIS ring was designed by NTT and manufactured by Hitachi. It is operating with three of ten planned beamlines working. This ring will be used for the future XRL work when a new stepper is completed. The Super-ALIS is reported to be highly reliable and meets all specifications except beam current, which is about 50% of the final goal. It was stated that there have been no critical failures on the Super-ALIS over the past year.

NTT has completed one stepper, which is operating on the NAR. The X-ray beam is scanned by a moving mirror in the beamline and the exposure field is 20 mm x 20 mm. Exposure is in air. A second-generation stepper, which will be installed on the Super-ALIS, is under test. Key features include air-bearing slides and lead screws and a dual-frequency heterodyne alignment system. The second stepper will have an exposure field of 25 mm x 25 mm.

It was stated that Fujitsu and Toshiba will have beamlines in the near future at the NTT facility.

NTT set the early standard for XRL mask technology in Japan. The membrane is SiN_x (2 μm thick, "x" is approximately 1.0) and the absorber is Ta (0.65 μm thick). One interesting aspect is the delay in back-etching the substrate until after the mask pattern is created. This simplifies the e-beam exposure and RIE etch of the absorber. By controlling stresses in both the membrane and absorber, the final mask distortion can be lower than that resulting from creating the free membrane before patterning. Overlay on the masks is reported to be 0.1 μm or better.

Although there is a growing interest in SiC, several other companies are currently using the NTT SiN_x mask process. NTT believes that SiN_x is suitable for manufacturing use and that SiC still faces several process technology difficulties.

NTT has built working 51-stage ring oscillators with 0.2 μm gate lengths patterned by XRL, and it is working on LSI level test fabrication in which larger-scale test patterns less than 0.2 μm are used as the supporting vehicle.

Initial work has started on projection XRL using a Schwarzschild-type lens with 8:1 reduction. Work is underway at the KEK Photon Factory to evaluate the multilayer mirrors and masks. Reflectivity of the Mo-Si multilayer mirrors is reported to be up to 50% at normal incidence.

In answer to our question on when XRL would be used, the NTT response was 1998 for the 256 Mbit DRAM era.

NTT does not directly operate any production wafer fabs. X-ray lithography technology will be licensed to semiconductor and system manufacturers who make circuits for NTT systems, and the technology could be licensed to other companies.

Site Visited: **Hoya Corporation**

Submitted by: K. Davis

Date Visited: October 31, 1990

Persons Contacted: Dr. Yoh-Ichi Yamaguchi
Manager, Thin Film Section
Mat rials Research Laboratory

Minoru Sugawara
Thin Film Section
Materials Research Laboratory

Hoya Corporation, a $1 billion company specializing in glass products, has 15% of its business in photomasks for microelectronics fabrication and other electronics-related glass products. Hoya is the largest supplier of IC mask blanks in the world, holding approximately a 70% share of the world market.

Hoya's Thin Film Section of the Materials Research Laboratory, a 5-person group responsible for X-ray mask technology, constitutes Hoya's entire X-ray lithography research effort.

The Hoya group initially began research on silicon nitride masks, but became concerned about radiation degradation and switched their entire effort to silicon carbide (SiC) membranes. In response to a question about other companies developing silicon carbide, Dr. Yamaguchi responded that he believed silicon carbide is of interest to all Japanese companies, but the historical NTT emphasis on silicon nitride continues to have a big influence on many companies in steering their efforts toward silicon nitride in the near term.

The Hoya membranes are deposited using hot-wall, low-pressure chemical vapor deposition (LPCVD). Internal stress is controlled (to 10^9 dyne/cm^2) by growing silicon-rich films, resulting in mixed poly Beta phase SiC and poly Si. Surface roughness of approximately 50 nm was measured, but the Hoya researchers believe roughness of less than 20 nm will eventually be required for X-ray masks. They don't see potential for polishing the SiC, but suggest the smoothness improvements will have to be achieved through deposition refinements, e.g., single crystal Beta phase SiC. We were shown a 3 cm x 3 cm membrane in a 3-inch silicon wafer mounted with epoxy on a Pyrex frame. The membrane appeared uniform and smooth, but slightly bowed. Hoya intends soon to send samples of SiC masks to SORTEC for radiation testing and alignment experiments. Preliminary life-test measurements using 20 KeV electron beams showed no observable stress change in 2 μm thick SiC membranes for up to 120 MJ/cm^3 of absorbed energy (equivalent to 240,000 X-ray exposures). When asked about diamond membranes, Dr. Yamaguchi said his staff were so far just planning diamond work, and expected to begin preliminary experiments with other companies' instruments by 1991. They expressed strong concern about the surface roughness of diamond membranes, however. A good reference which describes Hoya's SiC membranes is *Microelectronic Engineering 11*, pp 237-240 (Elsevier Science Publishers, 1990).

Hoya's current absorber material is amorphous tantalum boride (Ta_4B), deposited by rf magnetron sputtering, and it uses subtractive patterning by ECR plasma etching in chlorine gas. Our hosts argued that additive patterning using a wet plating process doesn't mate well with VLSI technology. They expressed concern that the amorphous Ta_4B may not have enough stability, and a switch to polycrystalline material may be necessary in the future. They are currently evaluating sputtered tantalum (Ta), with a goal of a very small (<0.1 μm) grain size and high density. A good description of Hoya's Ta_4B absorber films is contained in *J. Vac. Sci. Tech.* B7:1561-64 (Nov/Dec 1989).

Although Hoya's current glass frame mounting is by epoxy, its researchers are experimenting with anodic bonding, which they believe will be better. They are also experimenting with etching the silicon wafer (to form the membrane) after mounting the wafer, but currently they mount after etching. The Hoya glass materials group has recently developed a new glass, called SD-1, whose thermal expansion coefficient is better matched than Pyrex to silicon over the 50-500°C temperature range. We were shown a specification sheet for SD-1, which will be offered for sale commercially by the Optical Division in early 1991.

Hoya has already sent mask samples to Japanese, European, and U.S. potential customers (including Hampshire Instruments and DuPont, and it has had discussions with IBM and Motorola). The Hoya Electronics Division has ordered equipment for producing SiC films and plans to begin processing during March-May 1991. It expects to begin production by summer, 1991. Hoya will sell membranes with or without absorber, before or after etching and bonding. The Electronics Division also plans to upgrade its e-beam capability to be able to write 0.25 nm X-ray mask patterns. In response to a question about business growth, Dr. Yamaguchi said that X-ray lithography development in the semiconductor industry is proceeding slowly, but eventually Hoya expects a big market in X-ray masks--much more than 10% of total mask sales.

Site Visited: **Dai Nippon Printing Co., Ltd.**
Micro Products Division

Submitted by: H. I. Smith

Date Visited: October 31, 1990

Persons Contacted:

Kousuke Hirabayashi
Vice President
Micro Products Div.

Yoshio Hashimoto
General Manager
Research & Development

Seiki Nagao
Sales Director
Micro Products Sales Dept. Div.

Hiroshi Watanabe
Sales Department R&D

Yukio Iimura
Researcher
Micro Products Research Lab

Hiroyuki Miyashita
Research Engineer
Micro Products Research Lab

Tomihiro Nakada
Manager: Section 1
Micro Products Research Lab

Dr. Hisatake Sano
Senior Research Scientist
Micro Products Research Lab

Dai Nippon Printing Company is the world's largest all-around printing company, with annual sales in 1990 of ¥956.7 billion ($7.7 billion). The Micro Products Division has a strong position in the photomask business, with a fully automated production line. It has more than 10 MEBES-3 electron-beam pattern generators. We were not able to see the laboratory where photomasks and X-ray masks are made. Instead, we had a full and frank discussion at corporate headquarters with a team of technical people headed by Dr. Sano, and several high-level managers.

Dai Nippon has been making X-ray masks since about 1974, shortly after X-ray lithography was introduced in Japan. Discussions centered around an oral presentation by Dr. Sano of the prepared answers to the set of questions we had sent. Dai Nippon is aware of the advantages of X-ray lithography and is rather sophisticated in its development of X-ray masks. It had licensed mask technology from NTT several years ago and followed the NTT lead with SiN_x membranes, Ta absorber, and a process which is called Ta patterning, prior to formation of the membrane. DNP staff are trying to evaluate the limitation of NTT's prescription, especially of the pattern placement accuracy (some work was presented at the 1990 Micro Process Conference); the result might lead them to deviate from the prescription and to pattern directly on membranes. They believe SiC or diamond will replace SiN_x eventually. They recognize the value of optically flat mask membranes and are heading in that direction so that small gaps (less than 10 μm) can be used in the future. Despite their sophistication with regard to X-ray mask technology, personnel at DNP have themselves done only a few X-ray exposures.

Dai Nippon has all the state-of-the-art tools to make X-ray masks and staff were not worried that someone might jump way ahead of them in the technology. They believe they can catch up to any such development very quickly. Their views on X-ray lithography were generally consistent with those held at the other places visited. They do not believe it will be used in the 64 Mbit memory but instead for the 256 Mbit in 1995-96. They are now working hard on phase shift optical masks and believe this might further push the horizon for X ray to finer linewidths.

Dr. Sano believed that the major cost in X-ray masks will be the costs of e-beam lithography and inspection, and that these costs will come down with experience and demand. Our hosts said they have 10 MEBES e-beam machines but believe a round beam system will be needed to make good X-ray masks. They told us there are two suppliers of X-ray masks in Japan (Dai Nippon and Toppan) and three suppliers of mask blanks (Hoya, Shinetsu Kagaku, and Hitachi Metals). Dr. Sano believes that in order for X-ray lithography to be accepted in the IC industry, someone will have to build a competitive high-density DRAM with X ray. In addition to DRAMS, Dai Nippon was also interested in certain niche applications of X-ray lithography that require large areas of very fine patterning.

Presently, DNP is mounting a major effort in the fabrication of optical phase shift mask technology, and about 70% of its research and development effort is directed to this newly demanded technology.

In summary, DNP was highly knowledgeable about XRL; however, it can only respond to customer requests.

Site Visited:	**Hitachi Central Research Laboratory**
Submitted by:	J. T. Clemens
Date Visited:	October 31, 1990
Persons Contacted:	Dr. Shojiro Asai Deputy General Manger of CRL Mr. Shinji Okazaki ULSI Lithography Processes Dr. Shigeo Moriyama X-ray beamline and steppers Dr. Kazuo Hiramoto SOR ring issues Dr. Takumi Ueno X-ray resist issues Dr. Norio Saitoh E-beam machine design and development Dr. Kozo Mochiji X-ray masks and resist materials Mr. Iaro Ogawa X-ray processes (masks, resists, etc.) Mr. Hiroaki Oizumi X-ray mask technology Toshio Kaneko Marketing Engineer Semiconductor Equip. Design Dept.

The Hitachi Central Research Laboratory is a very large complex of buildings located on a large plot of land (215,000 sq. meters).

Personnel (Estimates): Total approx. 1300

With about 450 technical personnel involved in electronics

After a short period of formal introductions, Dr. Asai joined the meeting and reviewed the present Hitachi position on proximity X-ray lithography. He stated that after several years of active research, the decision had been made to reduce the level of research and development in this area. He stated that optical lithography appeared to have a rather long future, and that there existed various technical issues that needed to be addressed.

He furthermore stated that a small group of researchers would continue to investigate proximity X-ray lithography, in case the technology proved successful. Thus the Hitachi R&D organization could quickly reenter the technology development. This opening statement clearly stated the Hitachi strategy and set the tone for the rest of the discussion in the afternoon.

Technical Summary of the Discussion

The technical discussion consisted of several different segments. First, we were given a set of published papers that covered such activities as (a) construction of a z-pinch plasma X-ray source and aligner, (b) alignment system development, (c) X-ray resist characterization, (d) mask technology development efforts, and (e) exposure activities on the KEK Photon Factory synchrotron.

Second, Dr. Mochiji described the work on X-ray masks. Since much of the work has now been terminated, his review consisted mostly of published results. The membrane technology work was of highest priority and the discussion focused on the effects of oxygen incorporated into SiN structures, and the effect on radiation hardness. Furthermore our hosts stated that they had not yet started to research SiC or diamond membranes. It was very clear that the entire program had been scaled down significantly.

Third, there was a review by Dr. Hiramoto of the development of a precision diamond cutting tool for the fabrication of X-ray mirrors. The mirrors were machined out of oxygen-free copper and had a surface roughness of approximately 400 angstroms (peak to peak), while the goal was 200 angstroms. The work was parallel to similar activities reported in the literature; however, it did demonstrate the quality of the technical work. The mirrors were used in an experimental system that was located at the KEK Photon Factory. The exposure station used a small Be window that was roughly 20 μm thick and 7.0 mm x 40 mm, and this window was scanned along with the X-ray beam during exposure. This approach is to improve the reliability of the Be window against rupture.

Fourth, Dr. Saitoh reviewed the general activities of Hitachi in the development of electron-beam machines. Presently, Hitachi is moving into the e-beam machine market and hopes to obtain a dominant market share. He outlined Hitachi's present strategy, but the JTEC team was told that details of the strategy were company-private. The information provided showed that Hitachi believes that e-beam lithography is one of the most critical and difficult technologies associated with the manufacture of integrated circuits, and staff are aggressively attacking the technical issues.

Fifth, Mr. Okazaki gave a review of the present activities in optical phase shift mask technology. This technology appears to extend the range of optical lithography, but as we found in all our discussions of this subject, the most difficult issues, associated with arbitrary shapes, have yet to be addressed. Based upon the other discussions during the afternoon it appeared that work on phase shift masks was growing rapidly and that Hitachi was not withholding any information on any accomplishments or breakthroughs.

After the presentations, the JTEC team reviewed the list of questions that we were using as a structured interview form. The following information was obtained and helps to understand the overall picture of proximity X-ray lithography in Japan.

1. Hitachi is funding all of its research into the various forms of lithography.

2. It has only one member of its research staff assigned to the SORTEC consortium.

3. X-ray masks should be about 2.5 cm x 2.5 cm and need to be inspected to a defect size of 0.03 μm.

4. 1.0E6 to 1.0E7 exposures is the general goal for an X-ray mask.

5. 50-100 mJ/cm^2 resist sensitivity is required. This will require a chemically amplified resist material.

6. Gold is a poor choice of absorber material. It has a high thermal coefficient of expansion.

7. Electron-beam patterning errors must be no greater than 0.03 μm for 1x masks.

Site Visited:	**Toppan Printing Co., Ltd.** **Electronic Precision Components Division**
Submitted by:	H. I. Smith
Date Visited:	October 31, 1990
Persons Contacted:	Hiromitsu Fujiki Deputy Manager Photomask QC Osamu Masutomi Assistant Chief Researcher Katsuhiro Nakashima Manager of Overseas Sales Fuminobu Noguchi Assistant Chief Researcher Kazuo Suzuki Chief Researcher

Toppan Printing Company has 11,000 employees and annual sales of $6 billion. The Electronic Precision Components Division has been producing photomasks since 1961 and X-ray masks since about 1985. Originally, it obtained the technology from NTT through a technology transfer agreement. The technology was referred to as "second-generation," involving SiN_x membranes, Ta absorber, and a 3-level process for etching the Ta. Toppan has made several improvements on the NTT process, and unique variations (e.g., 2 mm thick Si mask substrates and UV cured bonding to a glass ring). It is presently working on processes compatible with 0.25 μm features and 50 mm diameter membranes. It makes its own materials except for SiC, which it buys from a Japanese supplier. Toppan has several people working on X-ray technology. They can call upon an enormous reserve of experience in making photomasks. It has a large number of e-beam lithography systems, an FIB repair tool, and arrays of inspection tools.

The Toppan people were extremely open with regard to problems in X-ray mask making and the approaches they will follow. They provided handwritten responses to our list of questions. They considered e-beam lithography to be the major problem in X-ray mask making. That is, existing tools do not have sufficient CD control or overlay. They believed adequate e-beam tools will be developed as the demand increases.

We were offered a walking tour of the laboratory but opted instead to watch a "video tour." The latter gave a very good picture of the high technical skills of Toppan.

We discussed the surprising amount of uniformity among the Japanese competitors in their approaches to X-ray mask making, which deviate significantly from IBM and Hampshire approaches. Most of this uniformity can be traced to the licensing of NTT technology. Another source of uniformity of approach (e.g., the belief that Ta is easier to etch than W) may be the existence of an informal study group on X-ray lithography within the Japan Applied Physics Society. We were told that this group exchanges information and ideas (e.g., the pros and cons of e-beam patterning before or after membrane formation). In the spring of 1991, there was to be a workshop (in Japanese) on X-ray lithography, with drafts to be published in Japanese.

Site Visited: **Mitsubishi Research Laboratory**

Submitted by: J. T. Clemens

Date Visited: November 1, 1990

Persons Contacted: Dr. Haruhiko Abe
Manager, LSI Process Development
Department #1

Dr. Yaichiro Watakabe
Manager, Beam Application Technology
LSI Process Development
Department #1

Mr. Toyoki Kitayama
Manager, Advanced Process Research Dept.

Dr. Nobuyuki Yoshioka
Engineer, Beam Application Tech. Group
LSI Process Development
Department #1

The members of Team A were met at the entrance to the new Mitsubishi research building by Dr. Watakabe, and were escorted to a conference room where we met the rest of our hosts. There was a brief presentation given by Dr. Abe, who then excused himself, due to a series of meetings that were being held that day.

The discussion that proceeded was sometimes vague, and several of our questions were not candidly answered, but this is not surprising since the Mitsubishi Corporation intends to manufacture X-ray synchrotron rings for commercial sale, and there is a natural tendency to keep detailed information private. Discussions were informative in many ways, and the visit was enlightening and worthwhile.

It is important to note that Mr. Kitayama had recently joined the Mitsubishi Corporation in the early part of 1990. He was formerly the manager of the NTT research effort in X-ray lithography at the Hon-Atsugi location.

Technical Summary of the Discussion

The technical discussion consisted of several different segments. In an initial discussion, our hosts stated that they had approximately 20 engineers working on X-ray lithography.

First, we were given a set of published papers that described research activities in (a) X-ray resist development, (b) X-ray mask development, and (c) fabrication of several device structures using XRL, including functional 1M DRAMs.

Second, we were given a perspective on the use of various forms of lithography for the fabrication of LSI devices, summarized as follows:

Lithography Technology		Design Rules	
optical	g-line	MCD > 0.70 μm	
	i-line	0.70 μm > MCD > 0.30 μm	
	KrF laser	0.35 μm > MCD > 0.25 μm	
	ArF laser	0.25 μm > MCD > 0.20 μm	
e-beam	variable shape cell projection	MCD approx. 0.25 μm	development and production
X-ray	proximity 1:1	0.25 μm > MCD > 0.15 μm	
	reduction 20:1	0.15 μm > MCD --------->	

It was interesting to note that our hosts at Mitsubishi were speaking of electron-beam technology, especially the cell projection technique, a technique Hitachi has advocated. It was not clear how seriously our hosts considered e-beam lithography for production, but they did have it on the chart they showed us.

Third, a review of the general design of the Mitsubishi synchrotron ring system was given. The basic X-ray source consists of three components:

LINAC	Energy = 20 MeV Current = 100 mA Length = 2.5 m
Booster Ring	Energy = 1.0 GeV Bending Radius = 2.23 meters Magnetic Field = 1.5 Tesla
Storage Ring	Type = superconducting Design = racetrack Energy = 0.80 GeV RF voltage = 100 keV RF frequency = 130 MHz

Fourth, a discussion of mask technology was conducted. Mitsubishi is presently using SiN membranes for its masks; but our hosts noted that materials such as SiC and DLC (diamond-like carbon) are important candidates. They use a tungsten-titanium absorber because of the ability to control the stress below 1.0 E+8 dynes/cm^2.

Fifth, our hosts noted that e-beam patterning of the masks was a major issue; consequently, they were working with JEOL to obtain an e-beam machine to perform the required patterning accuracy.

Finally, we learned some rather interesting pieces of information. SORTEC is an interesting issue. The original request for funding was $200 million, with the intention of building two types of storage rings, room temperature and superconducting. But the funding level that was granted by MITI was only $100 million. This amount just barely covered the cost of construction of a room temperature ring. Additionally, Mitsubishi is not planning on doing any serious work in projection X-ray lithography in the near future. Such work is being conducted by NTT and Nikon.

Site Visited: **Fujitsu Kawasaki Research Center**

Submitted by: G. Fuller

Date Visited: November 1, 1990

Persons Contacted:

Dr. Yasutaka Ban
Deputy General Manager
Corporate Technology Advancement Group
Fujitsu Ltd.

Mr. Kenji Sugishima
Manager, Advanced Technology Division
Fujitsu Ltd.

Mr. Toshihiko Osada
Senior Specialist
Technology Development Department
Advanced Technology Division, Fujitsu Ltd.

Mr. Kei Horiuchi
Senior Engineer
Semiconductor Devices Lab.
Fujitsu Laboratories Ltd.

Mr. Tokushige Hisatsugu
Fujitsu Laboratories Ltd.

Mr. Shigeru Okamura
Fujitsu Laboratories Ltd.

Fujitsu staff present for the meeting included representatives from Fujitsu Limited as well as Fujitsu Laboratories Limited, a separate subsidiary company located in Atsugi.

Fujitsu was established in 1935 and is a worldwide leader in information processing, telecommunication, and electronic devices, with annual sales approaching $20 billion.

The New Technology Center in Kawasaki was built to celebrate the fiftieth anniversary of Fujitsu. The 20-story building highlights the Fujitsu Kawasaki Research and Manufacturing Facilities, and supports a broad spectrum of R&D activities at Fujitsu.

Fujitsu Laboratories was organized in 1962 and became a wholly-owned subsidiary of Fujitsu in 1968. Fujitsu Laboratories "lead Fujitsu's R&D and are working on advancements in fields ranging from systems to nanometer technology." At the Atsugi facility, completed in 1983, the focus is on electron devices, electronic systems, and materials.

The XRL effort at Fujitsu is centered in the Advanced Technology Division of the Electron Devices Group, but there is not a specific XRL department.

Fujitsu XRL work presently centers around mask technology, beamline experimentation at the KEK Photon Factory, and device fabrication in Kawasaki.

The Fujitsu mask technology is unique and appears to be among the best in the world. The membrane is SiC, deposited by heteroepitaxy CVD, and the absorber is Ta with a stress-control argon ion implant. The back-etched membrane is mounted on a SiC support ring before patterning. Maximum distortion of 110 nm (3 sigma) over a 32 mm x 32 mm field has been demonstrated. As expected, no radiation-induced degradation was observed up to 90 MJ/cm^3. This would give a lifetime of at least 300,000 exposures. It was reported that hundreds of membranes have been made, and the yield is quite good.

One of the key problems with SiC technology. namely surface roughness, has apparently been solved by Fujitsu. The heteroepitaxy process at Fujitsu yields surface roughness less than 100 nm, much better than conventional CVD processes. Work is underway to further improve the surface for fine-line patterns. The SiC is basically single crystal, but has not been fully characterized.

Like many other companies, Fujitsu believes that good mask technology is the most important factor in the future success of XRL.

Fujitsu is currently using beamline 17C at the KEK Photon Factory and has a high performance rotating anode source in Kawasaki. The rotating anode source is unique, with the anode being a palladium-lined v-grooved disk. This combines the efficient palladium cone-shaped anode technology used in other locations with the high power capability of rotating anode technology.

The beamline at the Photon Factory is a two-mirror, low-pass filter design with a total length of 35 m. Due to the high output of the ring, a 50 μm Be window is used. This beamline is used for research on beamline components, resists, and masks, and does not yet have a stepper attached.

Fujitsu is planning to install a beamline on the NTT normal conducting ring in the next few months. It has no plans to add an SOR ring at the Kawasaki site. It is not actively involved in stepper development, although it built the stepper used for resist and device research in Kawasaki. The present stepper alignment is performed using a linear zone plate scheme, and the gap measurement uses a Moire fringe technique.

Fujitsu uses both in-house developed resists and commercially available resists for exposures. A Fujitsu shaped e-beam system is used, and it was reported that there are no serious problems due to heating or charging during the pattern writing. The patterning is performed on mounted membranes that have already been back-etched. Test patterns have been made as small as 0.15 μm line, 0.20 μm space, and working transistors have been built down to 0.20 μm gate length. Fujitsu has not yet built complex multilevel devices.

The lithography time line at Fujitsu shows i-line through 1994, deep UV from 1991 to 2000, and XRL beginning in 1996. It was stated that "hundreds of thousands" of working chips will need to be demonstrated before production engineers will accept the viability of XRL as a replacement for optical lithography.

Fujitsu believes it has solid mask technology and suitable resist technology. It is not developing production aligners or sources. The issue of warm versus cold ring has not been determined, but the source will be an SOR ring.

The number of people working on XRL is still quite low. Dr. Ban commented that the principal barrier today for all the major electronics corporations is hiring an adequate number of technical personnel.

Site Visited: **Matsushita Electric Semiconductor Research Center**

Submitted by: K. Davis

Date Visited: November 1, 1990

Persons Contacted: Dr. Toyoki Takemoto
Director
VLSI Technology Research Laboratory
Assistant Director
Semiconductor Research Center

Jyuro Yasui
Senior Research Engineer
Semiconductor Research Center

Dr. Noboru Nomura
Project Manager
VLSI Technology Research Laboratory

Yasuaki Terui
Senior Staff Engineer
VLSI Technology Research Laboratory

Matsushita is one of the largest electronics companies in the world. Consumer electronics products are marketed under many well-known brand names, such as Panasonic, Quasar, National, and Technics. Matsushita is also a leading semiconductor manufacturer.

Team A of the X-ray lithography panel visited the Matsushita Electric Semiconductor Research Center in Osaka. This center employs approximately 550 people divided among the VLSI Technology Research Laboratory, the VLSI Devices Research Laboratory, and the Opto-Electronics Research Laboratory. There are currently 5 people dedicated to X-ray lithography in Matsushita's VLSI Technology Research Laboratory. Matsushita's primary emphasis in X-ray lithography is on stepper/aligner technology and resists. It built the stepper for the SORTEC facility, which was delivered at a cost of approximately ¥600 million ($4.8 million). Many additional people worked on the stepper project. Matsushita is not working on synchrotrons or other X-ray sources, nor is it working on X-ray mask technology. There is effort on optical resist technology, particularly chemically amplified resist for excimer lithography, which is synergistic with the X-ray resist work. Matsushita plans to continue working with SORTEC in alignment, resist, and process development.

The SORTEC stepper features a high-precision, real-time, on-axis, die-by-die, full-closed alignment system and a vertical wafer stage that is operated in helium atmosphere. Matsushita researchers developed a 10-axis stage by combining a coarse XY positioning stage guided by hydrostatic air bearings and a fine positioning stage driven by 6 piezoelectric actuators. They are particularly proud of a novel holographic alignment error detection optics technique, which consists of a three-axis Fourier transform lens system. Mask-wafer alignment error can thus be detected during exposure and corrected by a servocontrol system. In this system, alignment precision (3σ) of 0.06 μm was achieved (not including wafer and mask errors). The exposure time in this system is 5 seconds. The stage speed is 200 mm/s, which is the same as Matsushita's g-line stepper. The alignment time is 400 ms, which is somewhat longer than optical steppers because of the need to clamp the stage. They typically work with a 20 μm proximity gap (adjustable between 10 μm and 50 μm) and have a maximum step field of 150 mm. The stepper is considered to be R&D equipment; Matsushita has no plans at present to announce a commercial X-ray stepper product.

As a semiconductor manufacturer, Matsushita believes that the optical lithography technology progression from g-line, to i-line, to KrF excimer is reasonable through 0.35 μm, but significant development is required beyond that. The staff anticipate that the applicable X-ray lithography feature sizes range from 0.25 μm down to about 0.1 μm. The product where X-ray lithography is most likely to first have an impact is the 256 Mbit DRAM, which will require 0.25 μm feature size and 0.06 μm overlay accuracy. Our hosts showed a chart indicating 256 Mbit DRAM investment beginning in 1995 and production in 1998, with either ArF excimer or X-ray lithography.

Site Visited:	**Toshiba ULSI Research Center, Kawasaki**
Submitted by:	A. Lepore
Date Visited:	November 1, 1990
Persons Contacted:	Dr. Tadahiro Takigawa Senior Manager Lithography Research Department
	Dr. Yoshio Gomei Senior Researcher Lithography Research Department
	Mr. Toshiaki Shinozaki Senior Research Scientist Process Research Department

Toshiba's net sales for fiscal 1989 totalled approximately $27 billion worldwide, with 31% from the consumer products, 19% from heavy electrical products, and 50% from information and communications systems and electronic devices. Sales from semiconductor devices were $4.2 billion, 15.6% of total net sales. Research and development expenditures totalled $1.7 billion, 6.3% of net sales, and were concentrated on memories, ASICs, and specialty ICs. Toshiba is the world leader in 1 Mbit DRAM sales with a 22.8% market share. In addition to memories, extensive product lines exist for discrete devices, power devices, logic and bipolar ICs, and Si ASICs. A new 4 Mbit DRAM mass-production facility has been built at the Oita plant in Kyushu, and a new facility for 4 Mbit and 16M bit DRAM in Yokkaichi will be completed in 1991. The ULSI Research Center is engaged in such projects as 64 Mbit DRAM, 2M pixel CCD, high-speed digital GaAs ICs, and HDTV image processor development, and it has a 400 m^2 Class 1 clean room.

Toshiba plans to have a beamline on the normal (NAR) ring at NTT Atsugi in the near future. It is a member of SORTEC and has also used the university beamline (#12C) at Photon Factory to study radiation damage in SiC masks. In considering its own SOR source, Dr. Gomei felt that a warm ring was superior, while Dr. Takigawa favored a superconducting ring. Toshiba would be able to build its own normal ring in 2-3 years given its experience in design and construction of the NTT NAR (normal) magnets. A superconducting ring would be purchased in low volume. However, Toshiba would consider building its own superconducting rings for larger volumes, although the magnet design would increase the project lifetime to 5-6 years. Since a production facility is expected to have 100 steppers, 3-5 rings may be required. Point sources were considered unsuitable due to power and reliability problems.

Mask research is increasing, as it is the major concern for X-ray lithography technology. 256 Mbit DRAM is expected to be ready for production before X-ray masks are ready. Toshiba's masks are based on a LPCVD SiC membrane (15 x 15 mm) and a W absorber. The priorities for improving masks are distortion, durability, and defects. The design stress goals are $< 1 \times 10^9$ dyne/cm^2 for the membrane and $< 1 \times 10^8$ dyne/cm^2 for the absorber. The mask is patterned after backside etching and mounted to the ring to minimize stress-induced distortions. Part of the concern for pattern distortion is that no high-accuracy electron-beam lithography system exists. A shaped electron-beam system is being developed at Toshiba that will have suitable positional accuracy. An X-ray microscope is also under development for use in mask defect inspection. Mask repair will be by focused ion beam, which will be a purchased system, possibly from JEOL where an experimental FIB repair tool is being developed.

The Mechanical Engineering Department is developing an experimental stepper. The current emphasis is on alignment (heterodyne), mirrors for beam scanning (in beamline), and Be window formation. The stepper has not been on a beamline yet but will go on the NTT NAR beamline soon.

In-house resists are being developed for excimer-laser deep UV and electron-beam lithography. The electron-beam resists will be extended for use with X-ray. Development of suitable resists is not expected to be a problem.

Toshiba plans to be able to use ArF excimer lasers and phase shift masks for minimum feature sizes below 0.2 μm. Optical lithography may be used for 256 Mbit DRAM since X-ray technology is not expected to be ready in time. X-ray lithography will be used for 1 Gbit DRAM production in 2000. Full implementation of X-ray lithography may require first exhausting the limits of optical lithography.

Site Visited: **Nikon Corporation**

Submitted by: M. Peckerar

Date Visited: November 2, 1990

Persons Contacted:

S. Yoshida
Senior Managing Director

S. Sasayama
General Manger
Design

H. Izawa
Senior Manager
Mechanical Design

T. Onuki
Manager
Technological Development

H. Nagata
Senior Manager
X-ray Group Leader

Nikon has maintained a long-standing interest in X-ray lithography, dating from 1977. It now maintains a staff of 20 people working in the field. Nikon has produced a number of prototype systems, all made at the Ohi plant. The major technical problem appears to be in the availability of the masks. Masks are 90% of the problem in achieving a viable X-ray technology. The official Nikon position is that optical lithography will be good to 0.25 μm (with high-NA lenses, somewhat shorter wavelengths, and possibly, phase-shifting). X-ray has a potential resolution advantage and a throughput advantage over e-beam. This will carry the technology through to the end of the decade. At that time, X-ray optical technology (primarily multilayer reflecting mirrors) will be available to create a reduction system similar to those under development at Bell and at Livermore. The company is also active now in designing alignment systems and gap controllers for X-ray proximity aligners.

MAJOR PROGRAM ELEMENTS

A. Next Generation Stepper. Nikon is working on optical subsystems for the next-generation (post-Matsushita) stepper for SORTEC.

B. Commercial X-ray Stepper. Nikon developed a commercial X-ray stepper using a conventional X-ray source a few years ago. Salient features of this design (as presented) are as follows:

Resolution: < 0.5 μm with positive resist (such as RE5000P)

Point Repositioning Accuracy: < 0.15 μm $\pm$ σ on bare silicon; 0.3 μm $\pm$ 3σ allowing mix and match errors

Ring Specifications: 0.5 mW/cm^2 yielding a 6 wafer/hour throughput with 21 stepper fields

Step-and-align times are currently 30 seconds, but Nikon researchers feel they must get below 1 second for a more practical system.

C. X-Ray Optics. There is a considerable effort here looking at novel reflector multilayers (many based on nickel: Ni/Va, Ni/Ti, etc., which gives almost 60% reflection for 8 KeV photons - possible for microscopy work). They have obtained 2 Å rms roughness on aspheric surfaces made on a unique platinum-coated Pyrex mandrel for a Wolter microscope optic. They feel that mirror collimators in the 10-14 Å wavelength range are not practical in the near term; for this reason, they favor synchrotrons as the source of choice. There is no company interest in plasma sources. Nikon researchers feel that they can build a 5X reduction ring-field scanner (17 mm ring arc, 0.1 mm wide) using 3 aspheric lenses in the 100-150 Å exposure wavelength range.

D. Miscellaneous Comments. They feel that for proximity printing, 10 μm is a reasonable mask-wafer gap. They feel that the total point repositioning accuracy for features on wafer should be 20% of the minimum feature size and that mix-and-match will not be useful (largely because of this 20% requirement). The primary need for X-ray technology is a supplier of good X-ray masks. There are no physical barriers to achieving this goal. E-beam technology can be stretched to do the job. E-beams would also be required for inspection and repair. They do not see a future for e-beams in direct-write production.

Site Visited: **Sumitomo Heavy Industries, Ltd.**
Quantum Equipment Division

Submitted by: D. Patterson

Date Visited: November 2, 1990

Persons Contacted: Mr. Atsushi Naitoh
Executive Managing Director

Mr. Eijiro Toyota
General Manager

Dr. Hiromitsu Nakabushi
General Manager, R&D Department

Dr. Hironari Yamada
Manager, R&D Department

Mr. Tsugu Kunio
Manager, Sales Department

Sumitomo Heavy Industries (SHI) has a hundred-year history building such products as ships, bridges, chemical plants, and forging machines. In 1989, 6000 employees from nine major divisions produced sales of $2.8 billion. The Quantum Equipment Group products include lasers and cyclotrons, as well as the synchrotron development done by its Tanashi (Tokyo) Works, as described below. During the 1970s, SHI made a cyclotron for the University of Osaka and helped in the construction of several national accelerator programs. In the mid-'80s they joined with Eaton (Cleveland, Ohio) to form Sumitomo Eaton Nova for the business of supplying ion implantation equipment to Japanese semiconductor manufacturers. These events provided the basis for an internally financed entry into the synchrotron business.

Sumitomo Heavy Industries activities in X-ray lithography center around its compact superconducting synchrotron AURORA and associated beamlines; for completeness, it is designing a stepper for "R&D" customers. SHI has successfully fabricated a unique (circular) superconducting magnet compact synchrotron, named AURORA. The 650 MeV electron storage ring has a bending radius of 0.5 m and critical wavelength is 1 nm. Having more than 100 tons of iron around the ring serves three purposes: magnetic shielding, radiation shielding, and reduction of forces between the coils. Sixteen ports radiate in three quadrants; one quadrant is utilized for injection and servicing. The massive piece of equipment breaks down into 5-ton components for shipping. For access to the internal works, it separates at the midsection and the top portion is lifted 50 cm by a built-in hydraulic system, all without warming the superconducting magnet. The irradiative power is 1.5 W/mrad at 300 mA stored current. Projected sales price of the production ring, with injector, is ¥2.5 billion. AURORA is the world's smallest synchrotron.

Injection is at 150 MeV from a racetrack microtron. Because of the lack of the straight sections most synchrotrons have, a novel injection scheme is required; the design uses a half-integer resonance perturbator. The 1 mA injection pulse of 1 μs at 10 Hz fills the beam in a few minutes. SHI designed and built the microtron and it has been the one area of difficulty in the program--after a one-year redesign, the injector successfully reached 1 mA current in September 1990.

SHI will supply beamlines, with the beam swept by an oscillating platinum (Pt) mirror on silicon carbide. For completeness, SHI is building a stepper for customers doing research and development. Wafer size is 100-150 mm; mask-wafer gap is 20, 30, or 40 mm; maximum field size is 25 mm x 25 mm; chromatic bifocus alignment gives 0.08 mm overlay; wafer ambient is air. Projected sales price is ¥80 million for the beamline and ¥200 million (rough estimate) for the stepper.

The system was just coming on-stream in the fall of 1990. The 100 mA current now has a six hour lifetime, reflecting the expected short beam life until the vacuum is aged. The projected beam life is 24 hours. Base pressure for the warm bore is expected to reach 1.0 E-10 torr (no beam). Beam position is very stable, even during ramp-up. The 40,000 l/s pumping system can evacuate to operating pressure in one day. Liquid helium consumption in the closed circuit is 10 l/hr. The magnets draw 1 Kw power, and RF power is 100 Kw. Projected maintenance is one week annually for cleaning the liquefier.

TABLE SHI-1
Key characteristics of Sumitomo Heavy Industries' Aurora Ring

Magnet	Superconducting (warm bore)
Energy	650 MeV
Field	4.3 tesla
Radius	0.5 m
Current	300 mA; 6.5 hr @100 mA, 3 hr @200 mA
Injection	150 MeV microtron, 1 mA, 10 Hz
Weight	180 tons
Size	2.7 m high, 3.4 m outer diameter
Beam Size	1.1 mm horizontal, 0.14 mm vertical
Projected Price	¥2.5 billion

Site Visited:	**Japan Synthetic Rubber Co., Ltd. (JSR)** **Electronics Research Laboratory**
Submitted by:	F. Pease
Date Visited:	November 2, 1990
Persons Contacted:	Kiyoshi Osada Manager, Research & Development Department Yoshio Matsumura Research Director, Electronics Research Lab. Toshihiko Takahashi Chief Scientist, Electronics Research Lab. Yoshiyuki Harita Manager, Electronics Materials Dept. Yoshiji Yumoto Chief Chemist, Development Center

Funding

JSR is the second largest Japanese supplier of photoresists (PR). Its sales of photoresists in 1989 totalled ¥3 billion, which is about 20% of the total Japanese market for photoresists and also represents 1.5% of JSR's total annual sales. JSR employs 3400 people and regards its photoresists business as one that will have significant growth. Total R&D expenses are ¥8 billion annually, but it was not clear how much of this was directed at resist R&D.

Key Elements

Although JSR has products in e-beam and X-ray resist (JSR MES-E and MES-X respectively) it is developing neither at present because it does not believe that either will represent a large business until after 1996 (based partly on a chart issued by SEMATECH).

Present Resist Products Include

1. JSR CIR family of cyclized poly-isoprene resists. These are negative photoresists with required doses as low as 1.5 mJ/cm^2 and low metal ion content to facilitate plasma ashing.

2. JSR MES-U resists. These are negative deep UV resists with a recommended dose of 7 mJ/cm^2 and "approximately 1/5 the dry etch rate of aluminum."

3. JSR PFR series positive PR with a required dose of about 20 mJ/cm^2 (420 ms in a GCA 4800 DSW).

<u>Development Resists (for 16 to 64 Mbit DRAM) Include</u>

1. For g-line, PFR GX-200, Gx250EL, 110DC8, and others. These show excellent imaging of 0.44 μm lines and spaces with exposure via a 0.54 NA lens.

2. For i-line, the PFR IX series of resists showing excellent imaging of 0.35 μm lines and spaces (NA=0.5) (Fig. JSR-1).

3. For 248 nm, PFR KRF-B7 showing well-resolved 0.3 μm lines and spaces in 1 μm thick resist (NA=0.42, 20 mJ/cm^2).

4. A surface-acting resist, JSR DESIRE, is also available and is targeted at the 16 Mbit DRAM.

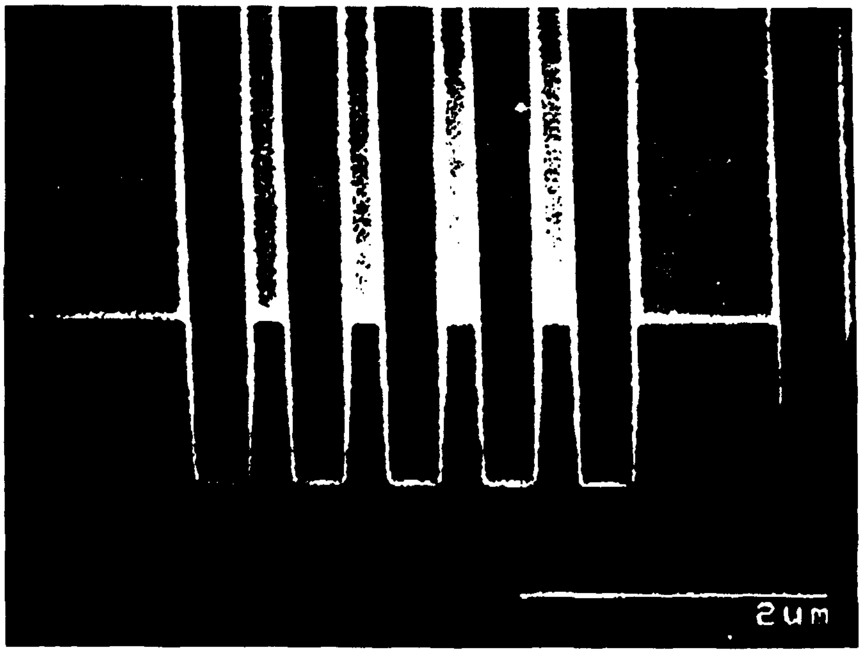


Fig. JSR-1. 0.35 μm lines and spaces imaged in JSR PFR-IX500EI positive photoresist (exposed with 365 nm light via lens of NA=0.50).

Site Visited: **Oki Electric**
Hachioji Facility

Submitted by: A. Lepore

Date Visited: November 2, 1990

Persons Contacted: Dr. Mukai
Director and Chief Engineer
(Meeting host)

Mr. Sakuta
General Manager
Semiconductor Research Laboratory
(Overall X-ray lithography program presentation)

Dr. Morifumi Ohno
(SOR source and beamline presentation)

Mr. Ohta
(X-ray mask presentation)

Dr. Ito
(Resist presentation)

Mr. Yamashita
(Phase-shift mask presentation)

In fiscal 1989, overall sales for Oki were $4 billion, with approximately $1.1 billion from telecommunications equipment, $1.8 billion from information processing systems, and $0.9 billion from electronic devices (23% of net sales). Research and development expenditures totalled $250 million. Oki's Miyazaki plant is currently producing 4 Mbit DRAMs [Editor's comment: the 16 Mbit DRAM production upgrades have been completed]. Oki's Hachioji facility is performing ULSI research for 256 Mbit and larger DRAM production with specific programs in X-ray lithography, deep UV lithography, and phase-shift mask technology.

It was indicated that the performance of the SORTEC ring has demonstrated that a normal SOR ring is a suitable production source due to the high stored current, stable beam, and reliable operation. Consideration will be given to a superconducting ring for production, due to the size advantage, if reliability can be proved.

X-ray mask development is underway based on a SiN membrane and a low-stress, high-density CVD tungsten absorber. The existing process involves absorber patterning prior to backside etching. Current emphasis is on controlling tungsten stress in the low 10^8 dyne/cm^2 range and on reducing critical dimension shift during reactive ion etching to less than 0.02 μm. This technology has demonstrated 0.2 μm line/space patterns and 0.2 μm holes in 5-6000 Å thick tungsten using an SiO_2 etch mask. Future emphasis will be on tungsten stress reduction to the low 10^7 dyne/cm^2 range.

Photo and electron-beam resists have been developed in-house, including i-line, KrF excimer laser, and Xe-Hg lamp deep UV resists, and positive and negative electron-beam resists. X-ray resists will be developed based on electron-beam resists and will be designed for single-layer use with SOR, 0.1 μm resolution, and less than 50 mJ/cm^2 sensitivity. Chemically amplified resists are being developed for electron-beam use and are expected to be the most promising for X-ray lithography.

Significant work in phase-shift mask technology was presented, excluding the areas of inspection and repair. Test patterns as small as 0.15 μm (isolated line and isolated space) have been demonstrated at i-line, with isolated via holes limited to 0.2 μm. Oki intends to improve upon these values using deep UV but our hosts did not specify expected minimum feature sizes. The difficulties of pattern layout, double-exposure technique, mask inspection, and mask repair associated with phase-shift mask production were acknowledged.

The process integration plan will use deep UV or i-line steppers with phase-shift masks for 64M DRAM production in 1995. A combination of optical and X-ray lithography will be used for 256M DRAM production in 1998. Oki plans to start constructing an SOR facility in 1995. Projection electron-beam lithography is also being considered for 256M or larger DRAM production.

APPENDIX F: STRUCTURED INTERVIEW QUESTIONAIRE

OUTLINE

- o GENERAL ISSUES - GOALS
  - TIME LINE
  - FINANCIALS
  - LIMITATIONS
- o GOVERNMENT / CONSORTIA
- o SOURCES
- o MASKS
- o BEAMLINES AND STEPPERS
- o PROJECTION X-RAY LITHOGRAPHY
- o RESISTS
- o SYSTEMS INTEGRATION, MANUFACTURING INSERTION

TOTAL QUESTIONS = 63

Questions

1. GENERAL

Q1 Why use X-ray lithography for manufacturing? What are the advantages?

Q2 When do you think that a manufacturing commitment to use X-ray for production will be made? What will be the product line?

Q3 How much money and how many people are working in Japan in the field of X-ray lithography?

Q4 What are the practical diffraction limits for proximity X-ray lithography?

2. GOVERNMENT / CONSORTIA

Q5 Is the Japanese X-ray program a national program and is it funded through the government or through a consortium of companies?

Q6 What is MITI's role in the X-ray program?

Q7 To what extent is the Japanese Government, e.g., through the Key Technology Center, assisting in the development of X-ray lithography technology?

Q8 How critical is the Japanese Government's X-ray lithography support to R&D in this area?

Q9 How are your research efforts at SORTEC, Tsukuba Photon Factory, and in-house laboratories coordinated with one another?

3. SOURCES

Q10 What type of source do you think will be used to produce products with X-ray lithography? Impact, plasma, or synchrotron?

Q11 If synchrotron-generated X rays are to be used; do you believe that the synchrotron will be a superconducting compact ring or a larger conventional ring with either cold or warm magnets?

Q12 What type of injection technology do you believe will be used for a synchrotron: a linear injector, or a racetrack type of injection such as the Sumitomo Juki injector or the Scanditronix injector?

Q13 How many ports do you believe a ring will have with steppers and beamlines installed on them?

Q14 What wavelength X rays do you believe will be used to expose semiconductor products with? Why?

Q15 How many X-ray lithography synchrotrons will exist in Japan in 1996?

Q16 Do point sources such as laser plasma or gas puff have a role in manufacturing? Why or why not?

Q17 What commercial application for synchrotrons might be feasible in addition to X-ray lithography?

Q18 What fraction of synchrotron development effort is financed by the Japanese government?

Q19 When will a compact synchrotron product for lithography be available for sale?

Q20 What is the present synchrotron status, i.e., stored current, lifetime, lifetime-current product?

4. MASKS

Q21 Do you believe that 1X mask technology is feasible?

Q22 Which parameters do you think are most important?

Q23 What is the most promising membrane material? What alternate materials should be pursued?

Q24 What are the preferred materials for X-ray absorber? For what reason?

Q25 How big a membrane field do you plan to use?

Q26 How and to what level will you inspect the membrane mask?

Q27 How will you repair the mask and with what tool?

Q28 To what stress level will the mask be fabricated?

Q29 Do you have a standard mask outline that you are planning to use and will there be a standard format for Japanese masks?

Q30 What is the minimum allowable mask-to-sample gap?

Q31 What is the strategy for mask patterning (i.e., what type of e-beam; whether master masks or daughter masks are used in manufacturing)?

Q32 Is your company developing mask technology? If so, what is the level of effort?

Q33 When will X-ray mask technologies be developed sufficiently for use in lithography systems?

Q34 What radiation effects have been measured in masks?

5. BEAMLINES AND STEPPERS

Q35 How will you scan the X-ray beam? With a mirror and optics box in the beamline, or will it be built into the stepper?

Q36 Who is building steppers and beamlines in Japan?

Q37 Will the beamline be tied into the ring control system or will it have its own system configuration?

Q38 What efficiency factor will the beamline with optics have?

Q39 What are the major technological problems with steppers, and approaches taken for solutions?

6. PROJECTION X-RAY

Q40 Do you believe that projection X-ray systems will be built and utilized before the year 2000?

Q41 What will be the wavelength of a projection X-ray system?

Q42 What will the mask construction look like for a projection X-ray system?

Q43 What kind of coatings will projection X-ray optics use?

Q44 What substrate material will the mask use?

7. RESISTS

Q45 What Japanese resist companies are producing resists that can be used for X-ray lithography and what are they?

Q46 Do you believe that special X-ray resists are required and if so why?

Q47 What do you think of using chemically amplified resists for X-ray lithography?

Q48 What technological developments are required before usable X-ray resists can become available?

8. SYSTEMS INTEGRATION; MANUFACTURING INSERTION

Q49 What are the principal barriers to *insertion* and use of X-ray lithography in semiconductor manufacturing?

Q50 What X-ray lithography technologies are being given the highest priority attention and why?

Q51 How is device and circuit fabrication integrated with your X-ray program?

Q52 Will special production facilities be built for the practice of X-ray lithography?

Q53 What level of X rays will be permitted outside of the facility (millirems per year)?

Q54 Will the area around the ring have to be evacuated for injection or will there be sufficient concrete to allow people in the area?

Q55 Has cost-benefit analysis been performed on the potential use of X-ray lithography in semiconductor manufacturing including factors such as facility cost, yield, and cost per chip? If so, how does X-ray lithography compare with competing technologies?

Q56 Is the introduction of X-ray lithography being targeted toward a specific semiconductor product? If so, what product? What year?

Q57 What is the anticipated time schedule for implementation of a complete X-ray lithography line for research and development? For full-scale production?

Q58 What will be the design and layout of a synchrotron-based semiconductor factory?

Q59 How is synchrotron reliability and down-time factored into factory design?

Q60 Will X-ray lithography eventually replace optical lithography or complement optical lithography?

Q61 If replacing, at what point (linewidth, integration scale, etc.) will X-ray lithography become necessary? When is this projected to occur?

Q62 If complementing, how would X-ray lithography be used in combination with other lithographies? When is this projected to occur?

Q63 How will the integration of individual X-ray technologies, such as sources, beamlines, steppers, masks, and resists, into a complete lithography system be accomplished?

APPENDIX G: PUBLICATIONS AND PATENTS ACTIVITY UNITED STATES AND JAPAN COMPARISON

D. J. Nagel

X-ray lithography research and development began in the early 1970s and has been actively studied in the United States for almost two decades. Researchers in Japan have been active in the field, publishing papers and obtaining patents, since the mid-1970s. This appendix presents the results of searches of annual publication and patent activity in the United States and Japan.

Three databases of DIALOG Information Services, Inc., were used in the search. Publications were counted from the Physics database INSPEC. Worldwide patent activity was tabulated from the World Patents Index. Patents in the United States were counted from the U.S. Patents Abstract Weekly database.

The table presents the results, with the numbers and fractions of the total publication and patents for the world, for the United States and Japan. Presumably, each of these presentations reflects the level of research and development activity worldwide and in the United States and Japan.

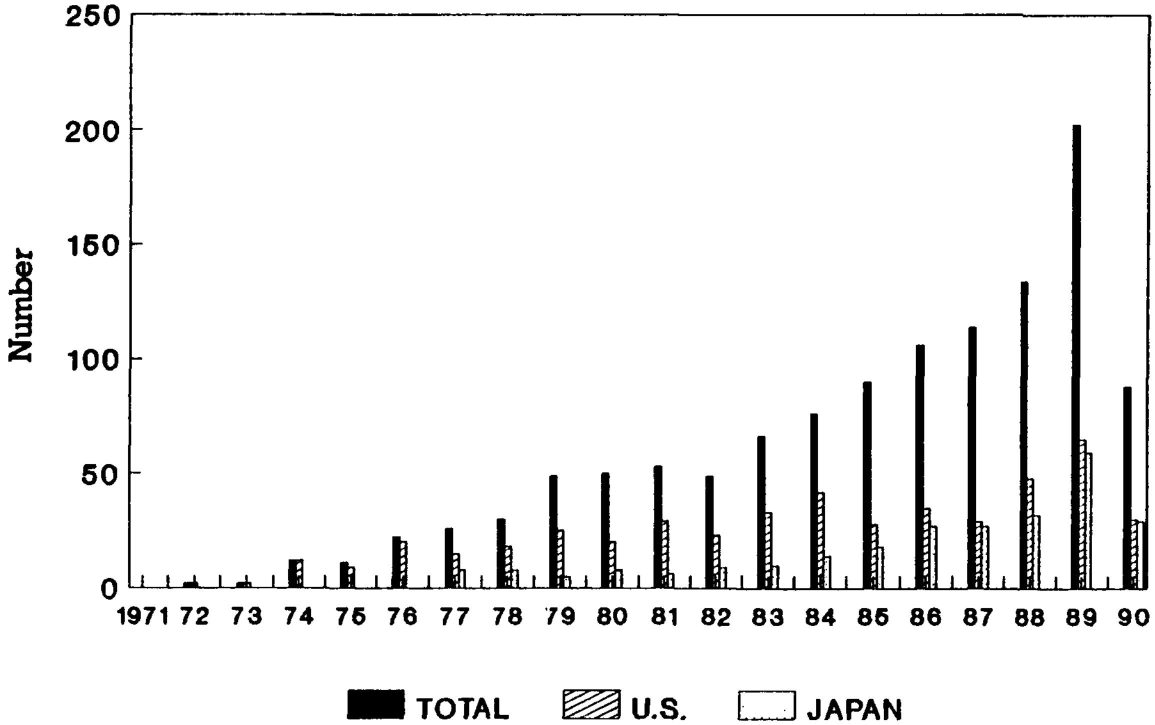
Graphical presentations of the data show trends as well as relative activity. The publication activity has tended to increase steadily. Publications from Japan started to appear about five years after publications from the United States and have run substantially below the U.S. rate until recently. Worldwide Japanese patent activity was below the U.S. rate until 1983. Recently, the Japanese have been granted many more patents worldwide than the Americans, with the Japanese worldwide total now over twice the U.S. total. The data, however, does not show patents which are multiply submitted in different countries; hence, it is difficult to draw definitive conclusions from this data. In the United States, the Japanese have filed about one-half the U.S. rate. This may indicate that the Japanese have embarked on an extensive global patent filing approach, while the United States has not.

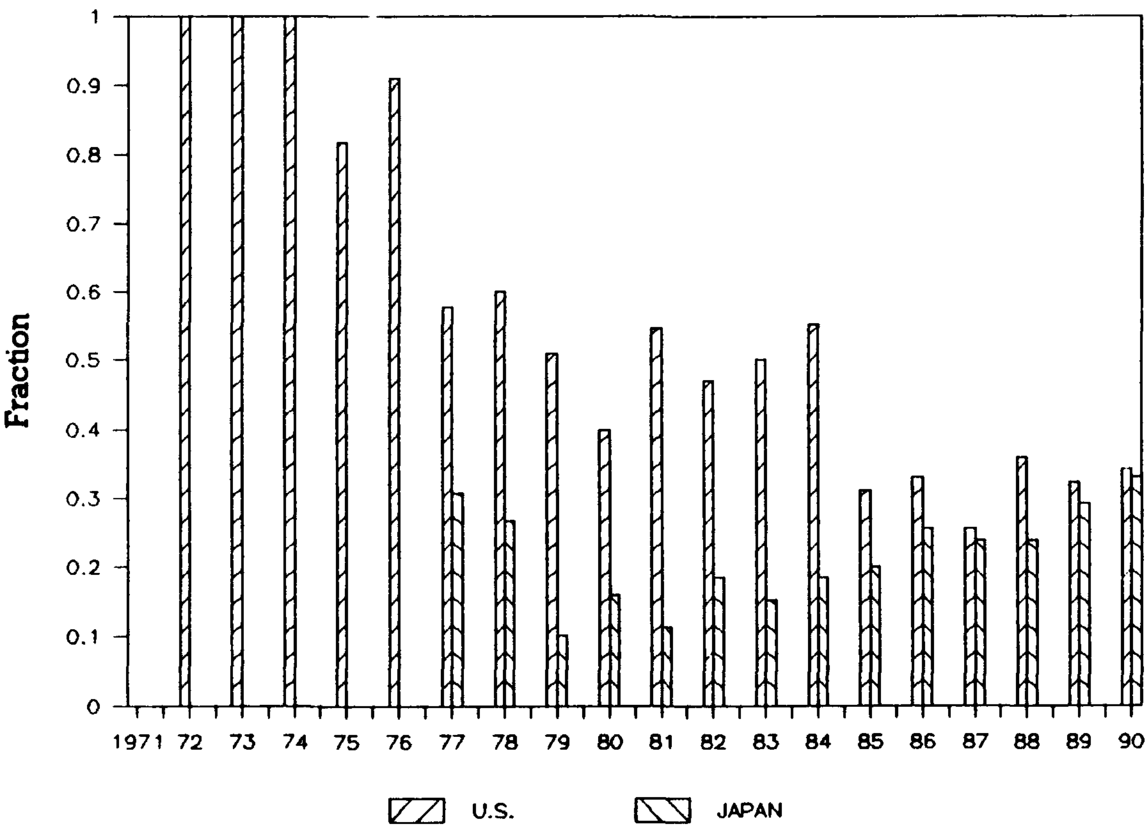
An overall view of the publication and patent data suggests (a) a large and growing interest in X-ray lithography on a worldwide scale; (b) major publication activity not from the United States or Japan (most probably from Europe); and (c) dominance of worldwide patent activity by the Japanese.

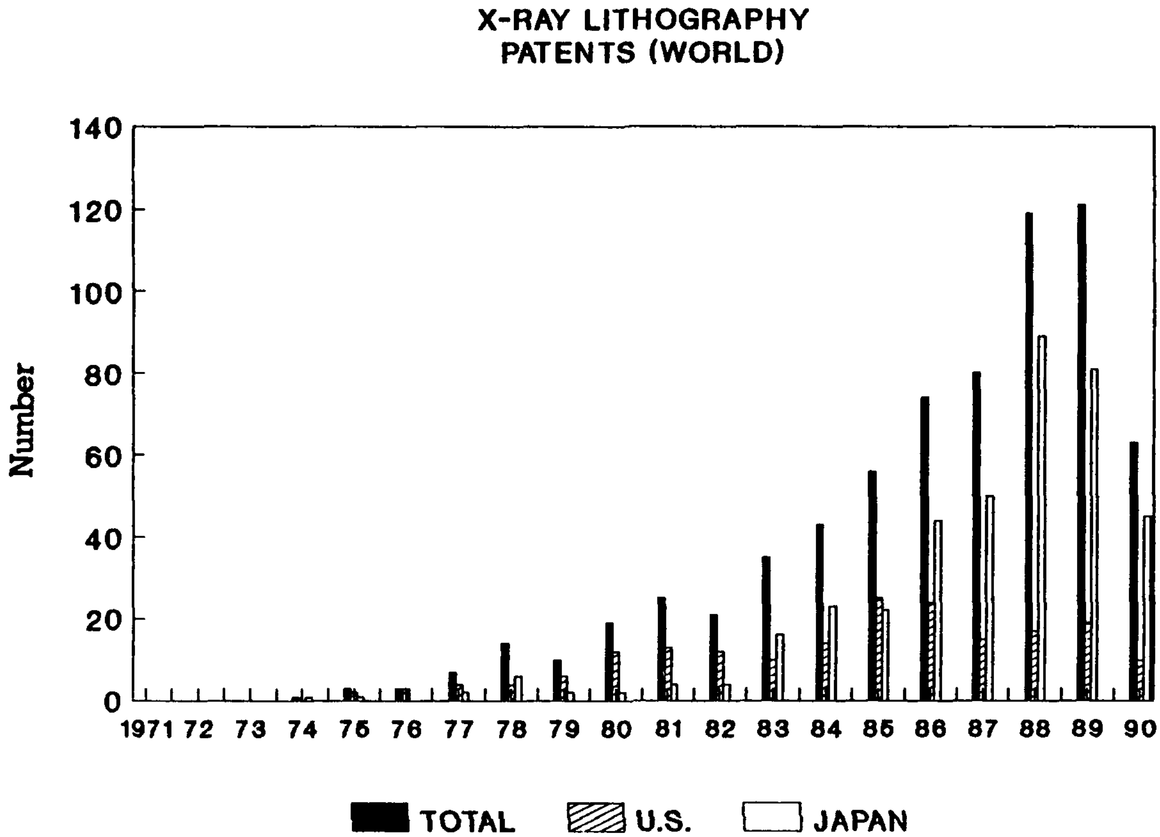
X-RAY LITHOGRAPHY
PUBLICATIONS AND PATENTS

	PUBLICATIONS					PATENTS (WORLD)					PATENTS (IN U.S.)				
		FROM U.S.		FROM JAPAN			IN U.S. 1ST		IN JAPAN 1ST			FROM U.S.		FROM JAPAN	
	TOTAL	NO.	FRACT.	NO.	FRACT.	TOTAL	NO.	FRACT.	NO.	FRACT.	TOTAL	NO.	FRACT.	NO.	FRACT.
1970															
1971	0	0	0.000	0	0.000	0	0	0.000	0	0.000	0	0	0.000	0	0.000
1972	2	2	1.000	0	0.000	0	0	0.000	0	0.000	0	0	0.000	0	0.000
1973	2	2	1.000	0	0.000	0	0	0.000	0	0.000	2	2	1.000	0	0.000
1974	12	12	1.000	0	0.000	1	0	0.000	1	1.000	0	0	0.000	0	0.000
1975	11	9	0.818	0	0.000	3	2	0.667	1	0.333	3	3	1.000	0	0.000
1976	22	20	0.909	0	0.000	3	3	1.000	0	0.000	2	2	1.000	0	0.000
1977	26	15	0.577	8	0.308	7	4	0.571	2	0.286	2	2	1.000	0	0.000
1978	30	18	0.600	8	0.267	14	4	0.286	6	0.429	2	2	1.000	0	0.000
1979	49	25	0.510	5	0.102	10	6	0.600	2	0.200	4	2	0.500	1	0.250
1980	50	20	0.400	8	0.160	19	12	0.632	2	0.105	9	7	0.778	1	0.111
1981	53	29	0.547	6	0.113	25	13	0.520	4	0.160	8	6	0.750	1	0.125
1982	49	23	0.469	9	0.184	21	12	0.571	4	0.190	7	7	1.000	0	0.000
1983	66	33	0.500	10	0.152	35	10	0.286	16	0.457	4	1	0.250	1	0.250
1984	76	42	0.553	14	0.184	43	14	0.326	23	0.535	6	5	0.833	1	0.167
1985	90	28	0.311	18	0.200	56	25	0.446	22	0.393	14	9	0.643	3	0.214
1986	106	35	0.330	27	0.255	74	24	0.324	44	0.595	15	13	0.867	1	0.067
1987	114	29	0.254	27	0.237	80	15	0.188	50	0.625	12	6	0.500	3	0.250
1988	134	48	0.358	32	0.239	119	17	0.143	89	0.748	5	1	0.200	2	0.400
1989	202	65	0.322	59	0.292	121	19	0.157	81	0.669	14	7	0.500	4	0.286
1990	88	30	0.341	29	0.330	63	10	0.159	45	0.714	9	5	0.556	4	0.444
SUMMARY	1182	485	0.410	260	0.220	694	190	0.274	392	0.565	118	80	0.678	22	0.186

X-RAY LITHOGRAPHY
PUBLICATIONS






X-RAY LITHOGRAPHY
PATENTS (WORLD)
Number
140
120
100
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1971 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
TOTAL
U.S.
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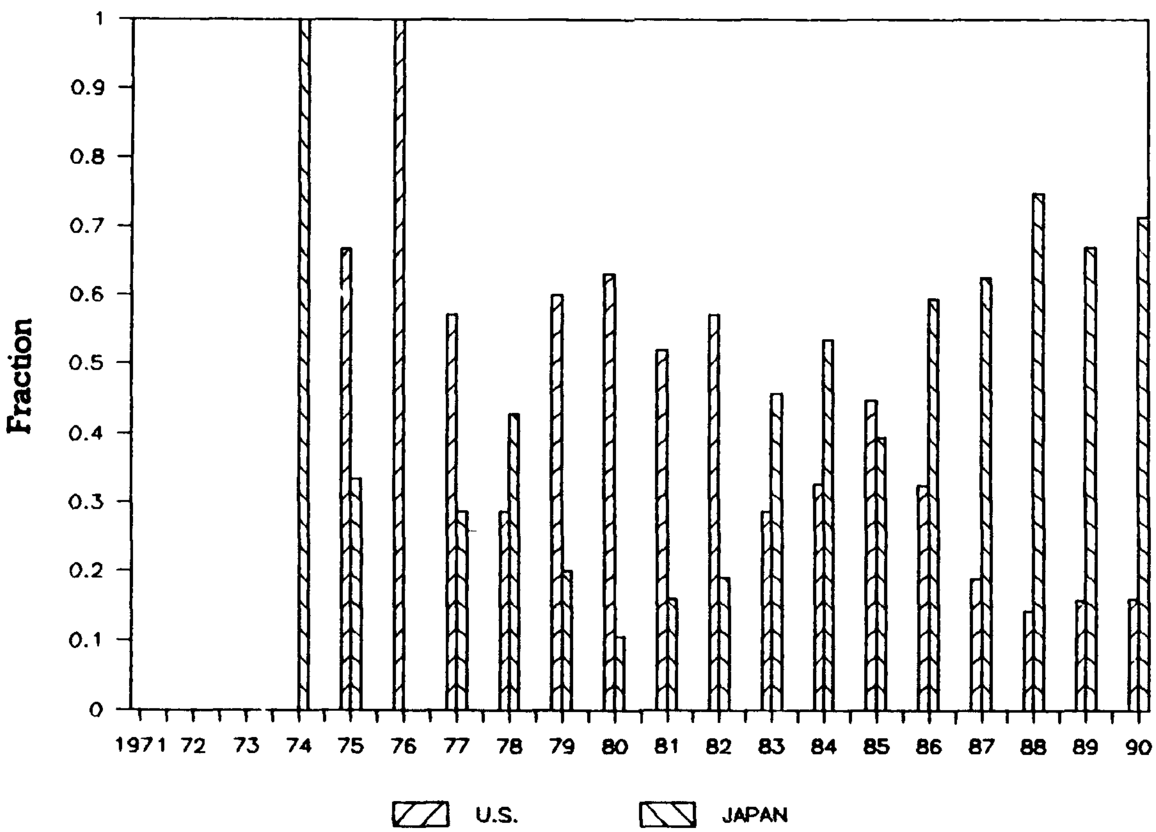
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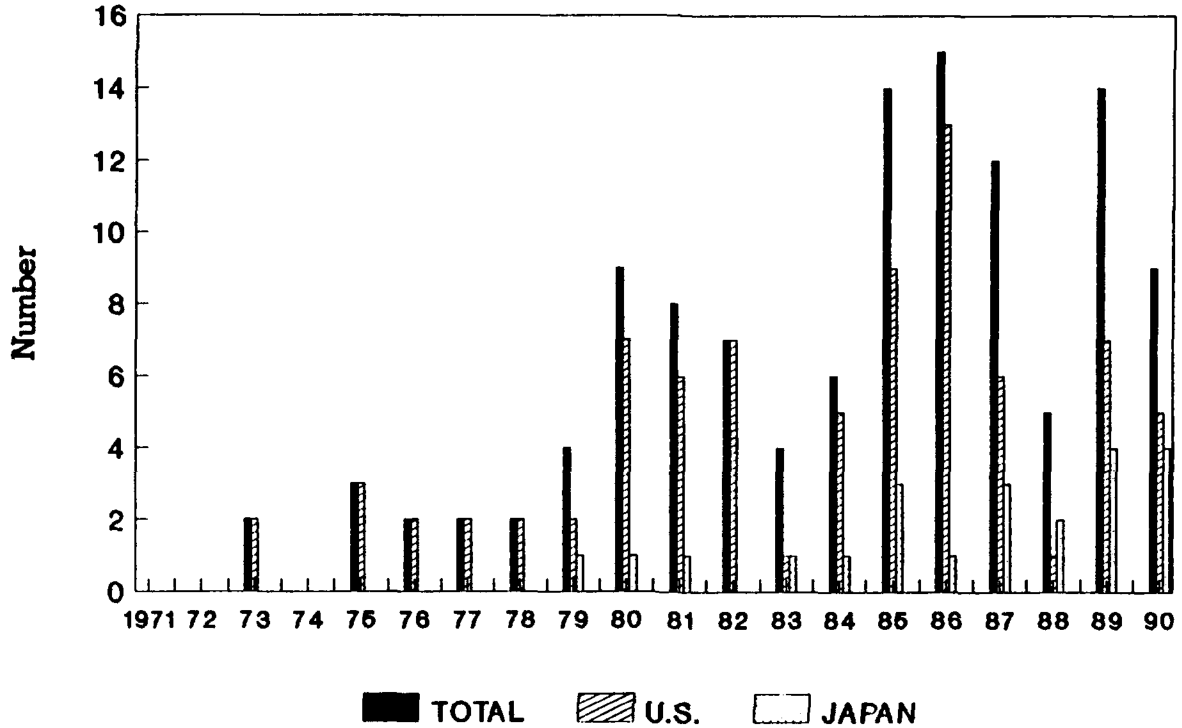

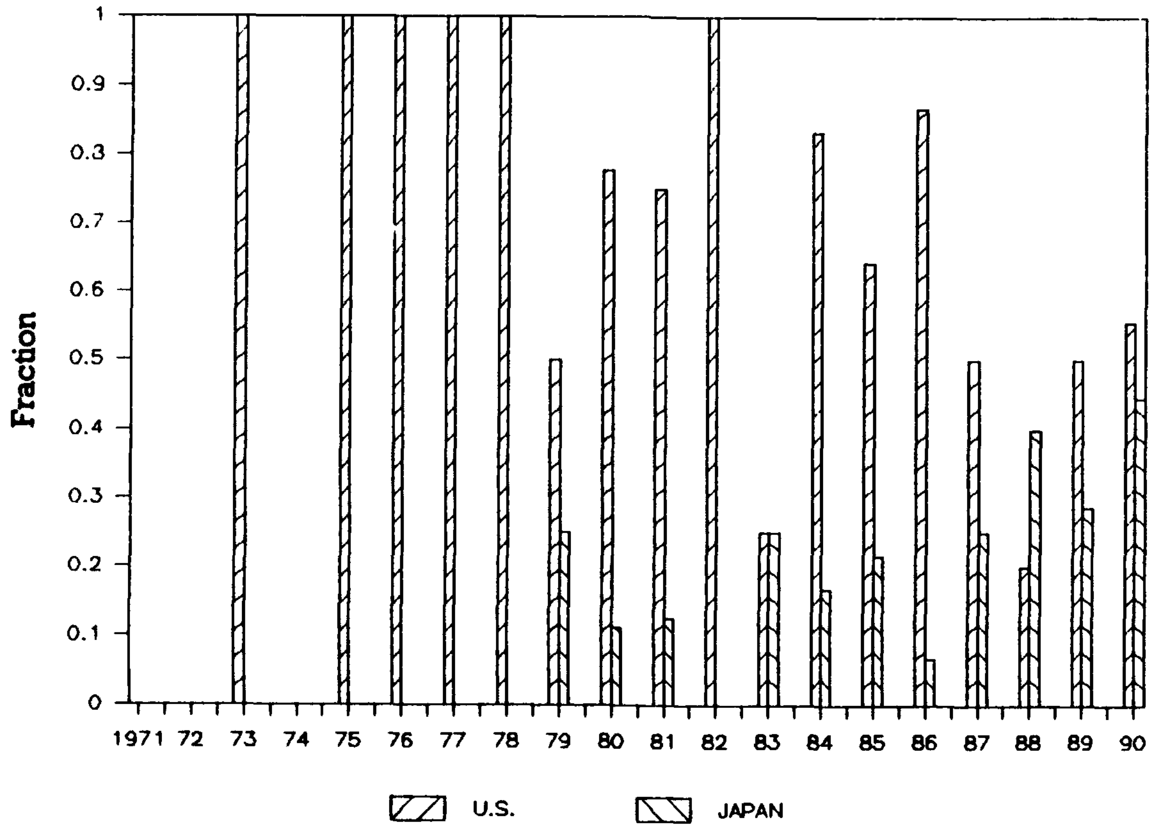

APPENDIX H: GLOSSARY

Aligner	Equipment used to precisely position a mask relative to a semiconductor wafer for the purpose of forming the circuit pattern in the required location on the wafer.
B-doped	Doped with boron.
Beamline	A hollow pipe used to transport X rays from an X-ray source to the aligner station. The beamline contains elements for shaping and controlling the X rays as needed for the lithography process.
Chloromethyl	A chemical group
CMOS	Complementary metal-oxide-semiconductor. A widely used type of semiconductor chip in which both p-type (positively charged, deficiency of electrons) and n-type (negatively charged, surplus of electrons) transistors are employed.
Defocusing	Putting out of focus--blurring
DRAM	Dynamic Random Access Memory. A widely used type of memory chip in which any unit of information can be addressed at any time. These chips are used in virtually all computers.
DUV	Deep ultraviolet
dynes	Unit of force, 1 gm cm/sec^2
E-beam	Electron-beam
EBL	Electron-beam lithography
ETEC	A company which makes electron-beam equipment (Hayward, CA)
Fiducials	A special reference feature placed on a reticle or mask used for the purpose of accurately positioning the reticle or mask in the aligner.

HMDS	A silicon-containing organic compound (Hexamethyl disilazane).
IC	Integrated circuit.
JEOL	A company which makes electron-beam equipment (Japan).
KeV	One thousand electron volts.
linewidth	The width of a feature in a transistor on a semiconductor wafer or chip.
Mask	A flat, transparent plate that contains the photographic image of wafer patterns necessary to define one process layer of an integrated circuit chip.
Mbit	Megabit. One million (actually, 1,048,576) units of information storage on a memory chip.
MFD	Minimum feature dimensions.
MIBL	Masked ion-beam lithography.
Micrascan	Trademark of advanced lithography tool made by JVC-L Corp.
Nanometer	One billionth of a meter (nm).
Novolak resin	A polymeric compound used in positive.
OL	Optical lithography.
orthogonal	Perpendicular to.
PAC	Photoactive compound
PBS	Poly butene sulfone
PDS	Poly (diphenylsiloxane), a silicon-containing organic compound.
Pixel	Picture element(s).

Photoactive	System the properties of which change on illumination.
Photoelectron	An electron ejected from a solid as a result of light bombardment.
Photolithography	Lithography based on photons (light).
Photoresist	A photo-sensitive emulsion used to define patterns on the wafer.
Resist	A photosensitive liquid film applied to the surface of a wafer for the purpose of capturing the image formed by X rays passing through a mask.
Reticle	Structure containing pattern to be imaged onto the wafer.
RIE	Reactive ion etching
Si-membrane	A membrane of silicon.
SiC	Silicon carbide.
SMIF box	A box with a clean environment in which wafers are stored or transported during the manufacturing process - frequently used to move wafers between clean areas or between machines.
SOR	Synchrotron orbital radiation.
Stepper	A type of aligner in which only a small portion of the entire semiconductor wafer is patterned at any instant. The entire wafer is patterned by sequentially positioning the mask and/or wafer ("stepping") to cover the full wafer area.
Submicron	Below one millionth of a meter.
Substrate	The silicon wafer upon which the chip circuits are fabricated. The term is used for both the initial starting silicon wafer and the partially completed wafer at a lithography process step.

SVG	Silicon Valley Group (Wilton, Ct.).
SVGL	Silicon Valley Group (Wilton, Ct.).
Synchrotrons	A circular system for accelerating electrons to high energy (10^9 eV).
torr	A measure of pressure.
μm	One millionth of a meter (micron).
Unnarrowed excimer	Excimer laser with no special means for narrowing the bandwidth.
Uptime	The percentage of time during which a piece of equipment or a larger system is ready to perform its intended function.
UTS	Ultratech Stepper System - a company
UV	Ultraviolet
VLSI	Very Large Scale Integration.
Wafer	A thin flat disk, typically silicon, used as the foundation for fabricating semiconductor chips.
Wafer fabs	A factory in which wafers are processed into semiconductor chips.
XRL	X-ray lithography.

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